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DOT/FAA/RD-82/33

Systems Research &
Development Service
Washington, D.C. 20590

Analysis of Active BCAS Alert Rates and Protection Based on Actual Aircraft Tracks

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February 1982

Final Report

U.S. Department of Transportation
Federal Aviation Administration

Technical Report Documentation Page

1. Report No. DOT/FAA/RD-82/33	2. Government Accession No. AD-A116402	3. Recipient's Catalog No.
4. Title and Subtitle Analysis of Active BCAS Alert Rates and Protection Based on Actual Aircraft Tracks		5. Report Date February 1982
		6. Performing Organization Code
7. Author(s) Lillian B. Zarrelli		8. Performing Organization Report No. MTR-80W267
9. Performing Organization Name and Address The MITRE Corporation 1820 Dolley Madison Blvd. McLean, VA 22102		10. Work Unit No. (TRAIS) 1491C
		11. Contract or Grant No. DTFA01-82-C-10003
12. Sponsoring Agency Name and Address Department of Transportation Federal Aviation Administration Systems Research and Development Service Washington, DC 20591		13. Type of Report and Period Covered Final
		14. Sponsoring Agency Code ARD-200
15. Supplementary Notes		

16. Abstract

This document describes an evaluation of the performance of the Active Beacon Collision Avoidance System (Active BCAS) using the Houston data base and simulated midair collision scenarios. The Houston data was extracted from ARTS III tapes and consisted of 65 hours of operation. This data was used to measure alert rates and assess desensitization techniques aimed at reducing the number of unnecessary alerts. The midair data base consisted of the reconstructed flight paths of 15 actual midair collisions. Measures of protection and tradeoffs were made based on the performance of the BCAS logic in resolving these simulated collision scenarios.

17. Key Words Active BCAS, Collision Avoidance, Midair Collision, Alert Rates, Desensitization, Performance Levels, RBX, Conflict Alert	18. Distribution Statement This document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	237	

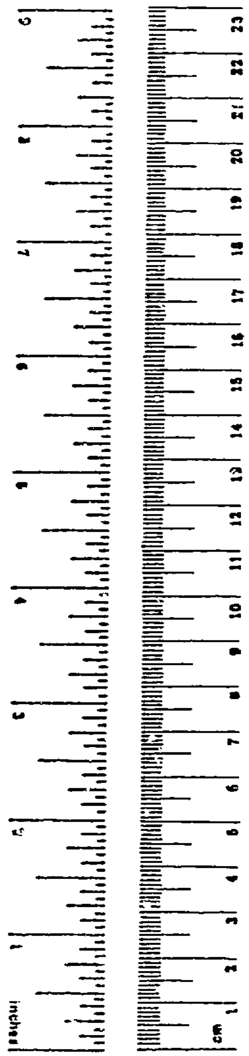
Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

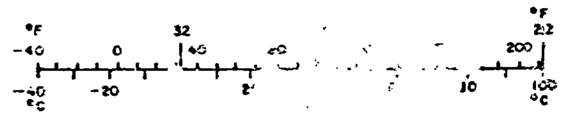
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

A note explaining the system context and publication date of this report is in order. The technical work described herein was performed during 1980, a year in which the Active Beacon Collision Avoidance System (Active BCAS) was under development. This concept included an airport-based Radar Beacon Transponder (RBX) that was capable of providing performance level commands to airborne Active BCAS units according to their range and/or altitude with respect to the RBX. These performance level commands established parameters in the Active BCAS logic by which proximate aircraft were determined to be collision threats or nonthreats. By proper selection of performance level commands, the threat detection logic could be progressively desensitized as the Active BCAS aircraft entered dense terminal airspace, thereby retaining a measure of collision protection without generating an unacceptably large number of nuisance or "unnecessary" collision alerts.

In June 1981, the Active BCAS concept was extended by the addition of technical features that would permit operation in high density airspace. This higher capability airborne collision avoidance concept is called the Traffic Alert and Collision Avoidance System (TCAS). TCAS does not envision the use of ground-based RBX units for sensitivity level control. Rather, sensitivity level will be controlled based on aircraft altitude, other aircraft inputs such as gear and flap signals and, perhaps, pilot inputs.

While the report focuses on Active BCAS and its RBX, its publication under the TCAS program is justified by the fact that Active BCAS Logic will be implemented in airborne TCAS units and the observation that the range/altitude desensitization functions of the RBX may be performed by selected Mode S ground stations. Moreover, the altitude-only desensitization functions discussed in this report are clearly relevant to airborne TCAS units.

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ACKNOWLEDGMENTS

The author would like to thank the many people who contributed to this document. Dr. Yan-Shek Hoh of The MITRE Corporation provided many Houston area plots of ARTS radar data. Dr. William Niedringhaus of MITRE updated the Monte Carlo Simulation for use in this analysis. Mr. James Grupe' of MITRE provided Conflict Alert results. Dr. Clyde Miller of the FAA and Dr. Al McFarland, Mr. Ned Spencer, Dr. Nels Broste and Mr. Andrew Zeitlin of MITRE provided much information and valuable insights.

EXECUTIVE SUMMARY

Prior analyses of the performance of the Active BCAS logic have demonstrated the need to eliminate the high incidence of unnecessary alerts generated in areas of high traffic density near airports. Most of the alerts close to an airport are due to normal traffic patterns, in particular, the near simultaneous landing of aircraft on parallel or intersecting runways. Unnecessary alerts which occur in a terminal area when a pilot is occupied with other tasks may be distracting.

Prior analyses have demonstrated that reducing the sensitivity of the BCAS parameters in order to reduce alert rate causes some tradeoff in separation protection. Inhibiting BCAS alerts entirely near the airport would mean that BCAS would not provide protection in some airspace where there was still a risk of midair collisions. No previous study has been undertaken to determine how the compromise between alert rate and protection can be optimally made. That is precisely the objective of this study.

The resources which were available to accomplish this goal consisted of two different sets of real-world data and several data analysis packages. The first data set consisted of 65 hours of ARTS III radar data collected over a period of ten days at Houston Intercontinental Airport. This data was used in conjunction with software which contained the Active BCAS collision avoidance detection and resolution logic. Tracks of all the aircraft pairs in potential conflict were used to drive the BCAS logic. All positive alerts which were generated as a result of exercising the BCAS logic on these tracks derived from real-world data were recorded.

The Active BCAS logic uses several sets of parameter values to provide different protection volumes in different airspace. Any individual set of parameter values comprises what is called a BCAS performance level. For the purposes of this study, BCAS has three performance levels in which alerts may be generated--level 3, level 4 and level 5. In addition, BCAS alerts are inhibited entirely in performance level 2. The protection volumes increase as the performance level number increases. An initial set of parameter values to be used for each of the three active performance levels was selected through sensitivity analyses. The variation in the number of alerts was noted as one parameter value was varied over its plausible range while the other parameter values were held fixed. The values selected for the parameters in each of the performance levels appear in the following table.

Performance Level	Modified Range TAU Threshold (Equipped Intruder) (sec)	Modified Range TAU Threshold (Unequipped Intruder) (sec)	DMOD (nmi)	ALIM (ft)
3	18	20	0.1	340
4	25	25	0.3	340
5	30	30	1.0	440, 640, 740

Once desensitized values were chosen for each performance level, the next logical step was to determine where the boundaries should be placed between each performance level region. Boundary selection was not simply a function of alert rate. Many individual conflict scenarios from each performance level were plotted and carefully analyzed to determine whether or not they justified an alert. No previous study has made extensive use of individual real-world conflict scenarios. Of particular interest were those alerts generated using one performance level which were eliminated at a less sensitive performance level. Care was taken not to extend desensitized regions too far at the expense of causing BCAS to give up a necessary alert.

Boundary selection was most critical between the performance level 2 region, in which BCAS alerts are inhibited entirely, and the performance level 3 region, in which the least protective parameters are used. Based on extensive use of individual conflict plots, the range and altitude boundaries between the regions were situated to maximize the protection area while eliminating most alerts which are due to normal traffic patterns. The boundaries selected were 2 nmi in range and 900 feet AGL. An additional function of the altitude boundary above an airport is to inhibit BCAS alerts against aircraft on the ground. It was found that the boundary between performance level regions 3 and 4 could be more flexible, being placed at a range on the order of 10 nmi from an airport. The boundary which designates performance level 5 is determined by altitude only. This performance level is employed in the region above 10,000 feet MSL.

In addition to desensitizing BCAS parameter values, logic updates were made which affected alert rate. A vertical divergence test was added to the logic which eliminates alerts for encounters involving aircraft which are diverging in altitude at the time of closest slant range. A second logic update was made which provided extra warning time against an unequipped intruder with a vertical closing rate. Although a few alerts were added as a result of this logic change, the added protection is worthwhile. The alert rate generated by the updated

BCAS logic, assuming that one aircraft in every conflict pair was not equipped with BCAS, was 64 alerts in 65 hours. The desensitized parameters and nominal performance level region boundaries described above were used to obtain this result.

Having made this tentative selection of parameter values and performance level region boundaries, an analysis of the protection tradeoffs caused by desensitization was begun. The data used was derived from the National Transportation Safety Board accident reports for 15 actual midair collisions that occurred since 1965. The midairs were selected because they were the only ones whose flight paths could be adequately reconstructed for the simulation. The accidents were grouped by the performance level region in which they would have occurred had the boundaries recommended above been in effect at the relevant airports. The selected parameter values appropriate to each performance level group were used in the analysis. In this way, the performance of the BCAS logic with respect to the selection of parameter values and performance level region boundaries could be evaluated from both the Houston and midair data. The Houston data showed how many unnecessary alerts could be eliminated with desensitized parameters, and the midair data showed how much protection would be given up with the same desensitized parameters.

A Monte Carlo Simulation program containing the Active BCAS collision avoidance detection and resolution logic was used to generate 20 randomly distributed variations of each of the 15 midair scenarios. In order to quantify protection tradeoffs in each performance level, comparisons were made of the minimum separations which resulted after simulating aircraft response to BCAS alerts. Each midair scenario was simulated three times--once with both aircraft BCAS equipped, once with the first aircraft equipped, but the second unequipped, and once with the equipage reversed. All encounters which showed poor separation were then individually reviewed to determine the cause.

The scenarios which showed poor results basically fit into two categories. First, there were those scenarios which failed for only 3 or 4 of the twenty repetitions. Those are considered to be the tail of the simulation distribution. There were several factors which were found to be responsible for the poor performance in some of these repetitions. High altimetry errors were found to be the most significant factor to hinder BCAS performance. Large errors can cause late alerts or ineffective sense selection. In addition, the collision avoidance logic was found to be impeded by lags in tracker response to a vertical maneuver at the moment that sense selection was being made by the BCAS logic. When the simulations were repeated using quicker pilot response and faster escape rates, noticeably improved separation resulted for these repetitions which represent the tail of the separation distribution.

The second category of poor results contained those scenarios in which a very abrupt high rate maneuver was initiated by the intruder aircraft. Two such vertical maneuver scenarios were found to be ineffectively resolved by the BCAS logic when one of the aircraft was unequipped. For the case in which the vertical maneuver was made by the unequipped intruder, most of the repetitions failed. In both scenarios the unequipped intruder achieved a vertical rate in excess of 3,500 fpm. Performance was reassessed using faster simulated acceleration, pilot response time, and escape rates on the part of the BCAS equipped aircraft. For one of the scenarios, increased escape rates by the BCAS aircraft significantly improved separation results. However, the second scenario showed only marginal improvement. Any collision avoidance system is limited in its ability to resolve encounters created by abrupt maneuvers on the part of unequipped intruders. It was shown that, in the case of a sudden maneuver, increasing the minimum warning time threshold does not effectively solve the problem. Sudden high rate vertical maneuvers by an intruder aircraft can cause the computed time to co-altitude to drop 15 or 20 seconds or more in just a second or two. Therefore, the additional warning time is insufficient to provide adequate separation.

For the case in which the abrupt vertical maneuver is made by the BCAS equipped aircraft, the results were more successful. Faster escape response by the maneuvering BCAS aircraft would provide even better protection. An aircraft capable of initiating an abrupt 3,500 fpm vertical maneuver should also be capable of rapidly achieving a high escape rate. In addition, the traffic advisory logic should aid by providing pilots with prior knowledge of the existence of aircraft in the vicinity.

Each of the 15 midairs was also simulated in a performance level other than its nominal one. By doing so, a determination was made as to the effectiveness of the selected performance level parameters and boundaries. As was expected, the scenarios experienced better separation when more sensitive parameters were simulated. Although this fact would seem to favor using more sensitive parameters, other factors were found which improved separation without increasing sensitivity and correspondingly increasing unwanted alerts. Larger escape rates and faster pilot response to a BCAS alert significantly improved separation for nearly all encounters. Notably, some of the scenarios with marginal performance involved a large commercial aircraft in conflict with a smaller general aviation aircraft. When the higher performance aircraft was simulated to be BCAS equipped, results were generally good. When the low performance aircraft was equipped but the larger aircraft was unequipped, separation was decreased.

The parameter values and performance level boundaries recommended by this study are thought to represent the best tradeoff between protection and unwanted alerts that can be arrived at through engineering study of the available data. It is important to confirm the effectiveness of BCAS when these parameters are employed by conducting appropriate operational evaluations.

CONCLUSIONS

1. The number of unnecessary alerts in the Houston data base has been significantly reduced as a result of desensitizing BCAS parameter values, inhibiting alerts close to the airports and adding logic updates. On the basis of careful review of approximately 60 individual encounters, it was concluded that virtually all of the alerts eliminated through desensitization were either unwanted or only marginally useful alerts. The current BCAS logic, which includes vertical divergence and unequipped intruder logic, generated 64 positive alerts in 65 hours of data. This number represents the alert rate against unequipped intruders.

2. Use of the selected desensitized parameter values of performance level 3, in conjunction with designating a 2 nmi range boundary and 900 foot altitude boundary for inhibiting BCAS alerts appears to have effectively eliminated unnecessary alerts close to the airport. At the same time, BCAS continued to alert for those conflicts which were judged to be truly dangerous. The Houston data showed conclusively that BCAS alerts must be inhibited within a small distance from an airport. Analysis of runway use at Houston and Hobby Airports shows that simultaneous use of both parallel and intersecting runways causes the generation of unnecessary alerts when such desensitization is not used. The recommended BCAS performance level region boundaries and parameter values satisfactorily eliminate alerts due to these routine operations.

3. According to the Houston data results, the 10 nmi inner boundary of performance level 4 and the lower 10,000 foot boundary of performance level 5 appeared to warrant some extension in order to reduce alert rates. However, Monte Carlo analysis contradicted this. The inner range boundary of performance level 4 cannot be extended much further than 10 nmi from an airport without noticeable loss in protection.

4. In an 'error-free' environment, simulating both aircraft in each scenario to be BCAS equipped resulted in satisfactory separation with one exception for each performance level run. The exception is the Carmel, N.Y. midair. The BCAS resolution logic is limited in its ability to protect against this collision geometry due to the abrupt vertical maneuver of one of the aircraft 15 seconds prior to the collision.

5. When simulation errors were introduced, and both aircraft were assumed to be BCAS equipped, the capability of the BCAS logic was

found to be limited in providing adequate separation only for the Carmel, N.Y. accident. The scenario involves a sudden 1/2 g vertical acceleration to 4,000 fpm at a time when the two aircraft were close in range. An important factor was found which could have improved the performance of this scenario. The traffic advisory logic, had it been simulated, would have displayed an advisory prior to the time of the vertical maneuver. If the pilots could have been made aware of each other's position it is possible that such a maneuver would never have been initiated.

6. When only one aircraft in a scenario is simulated to be BCAS equipped, two of the midairs show poor separation results. These are the Carmel, N.Y. and Urbana, Ohio accidents. In particular, several failure encounters occur when the low performance aircraft is simulated to be BCAS equipped while the high performance aircraft is simulated to be the unequipped intruder. The results are significantly better when the higher performance aircraft is simulated to be equipped. This is the equipage configuration most likely to be seen in the early stages of BCAS implementation. For the Urbana accident, the BCAS system is not effective when the aircraft that initiates the abrupt maneuver is unequipped. Simulation results show that providing a larger warning time in the case of such an abrupt maneuver does not significantly improve separation protection. However, an improvement in separation protection can be seen when faster escape rates and reduced pilot delay time are simulated. In both the Carmel and Urbana accidents, the suddenly maneuvering aircraft had vertical rates in excess of 3,500 fpm at the time the alert was generated. It is not infeasible then, to expect that if the aircraft initiating the abrupt maneuver were BCAS equipped it could initiate a high rate escape maneuver with equal abruptness. The conflict resolution would have improved significantly for the Urbana scenario if an escape rate of 1,500 fpm were used instead of 1,000 fpm. Improvement is not as dramatic for the Carmel scenario; however, some extra protection is provided.

7. When only one aircraft was simulated to be equipped with BCAS, the other midair scenarios were shown to be provided with adequate separation using conservative escape maneuvers, with a few exceptions. Several factors were found which contribute to reduced separation for some encounters, particularly in the performance level 3 region. Tracker lag in response to vertical rate changes was one factor. (The vertical tracker employed in this study was of the Alpha-Beta type with Alpha = 0.4, Beta = 0.05. Since this work was done, this vertical tracker has been replaced with one providing better transient response.) Increased accuracy in vertical tracking should improve BCAS sense selection capability for some failure scenarios, resulting in greater separation. Large altimetry errors, however, proved to have the greatest impact on performance by decreasing the effectiveness of the BCAS resolution advisories.

8. Pilot response delay and aircraft escape rates have a great impact on separation protection. When the midair scenarios of performance level 3 were simulated using quicker response and higher escape rates, significant improvement in separation was observed relative to the results obtained with conservative escape maneuvers. In fact, only 3 of the 300 repetitions of the 15 midair collision scenarios remained in the failure area of the scatter plot. Two of the scenarios were found to provide satisfactory separation when a logic change was implemented to inhibit the premature transition of a positive alert to a negative alert. When this logic change is implemented, only one failure encounter will remain. It is important that pilots be made aware of the manner in which quick response enhances BCAS performance.

9. Results of the desensitization analysis indicate that it may not be feasible for BCAS to protect against collisions like the one occurring at St. Louis. The St. Louis accident occurred at a range of 1.5 nmi from the airport. If BCAS were to operate at such a short distance from the runways, many unnecessary and distracting alerts would be generated. Awareness of the presence of the other aircraft from BCAS derived proximity information, however, may be beneficial.

10. The tradeoff between alert rate and protection is significant. It is concluded that the smaller performance level 3 parameters recommended in this study sacrifice a small degree of protection. However, using performance level 4 parameters in the performance level 3 region would significantly increase the alert rate.

11. Reducing the modified range tau threshold from 20 seconds for unequipped intruders to 18 seconds for equipped intruders in performance level 3 accounted for a 12% decrease in positive alerts. The Monte Carlo simulation results showed that the 18 second threshold produced adequate separation. Thus, this reduction seems quite worthwhile.

12. The inclusion of 1200-code aircraft in the Houston study had a significant effect on alert rates. Although 1200-code aircraft accounted for only about one eighth of the total instantaneous count of aircraft in the Houston environment, they were involved in 44% of the conflicts.

13. Due to the small number of high altitude alerts in the 65 hours of Houston data, there appears to be little need for providing command downlink capability to en route centers. However, it is recognized that terminal areas other than Houston may experience more en route activity.

14. Use of the range/altitude mapping capability for selec... BCAS performance levels would provide the flexibility needed to effectively tradeoff alert rates and collision protection at ... different airports.

15. Altitude-only desensitization is an alternative to using range/altitude information for desensitization. Altitude-only desensitization provides less flexibility and discrimination for airport-to-airport adaptation of performance level region boundaries.

16. A possible alternative to altitude-only and range/altitude performance level selection is an on-board automatic desensitization scheme. This would make use of a combination of barometric and radar altimeter signals and landing gear and flap signals to trigger performance level changes.

17. Only two multiple aircraft encounters were found in the Houston data base. One of the conflicts occurred inside the performance level 2 region, in which BCAS does not display alerts. The second encounter involved one aircraft simultaneously in conflict with two others. However, application of desensitized performance level 3 parameters eliminated one of the aircraft as a conflict, reducing the entire multiple aircraft encounter to one involving only a single conflict pair. The fact that any potential multiple encounters at all were found in the 65 hours of data attests to the need for a logic capable of handling them.

18. The per-aircraft positive alert rate averaged over the entire 65 hours of data is one alert in 12 hours for all aircraft types. For ATC-code aircraft only, the rate is one alert in 19 hours, and for 1200-code aircraft only the alert rate is one alert in 4 hours.

19. Results of the comparison between BCAS and Conflict Alert showed that both BCAS and Conflict Alert gave alerts on 19 of the encounters at Houston that involved only ATC-code aircraft. Conflict Alert gave an alert on 76 encounters for which BCAS did not. BCAS gave an alert on only 1 encounter for which Conflict Alert did not. In addition, 3 of the encounters for which both BCAS and Conflict Alert gave alerts were given earlier by BCAS. The most frequent reason for a BCAS alert occurring earlier is that, if the two systems detected a conflict at the same moment, a 3 out of 5 scan 'hit' requirement for Conflict Alert would delay the alert longer than a 2 out of 3 cycle BCAS 'hit' requirement. It appears that in a terminal area in which Conflict Alert is in operation, BCAS alerts will nearly always appear after a Conflict Alert since Conflict Alert is more sensitive to aircraft proximity than is BCAS.

RECOMMENDATIONS

1. The BCAS logic threshold values recommended as a result of this study are as follows:

Performance Level 3: TRTHR = 20 seconds for unequipped intruder
TRTHR = 18 seconds for equipped intruder
DMOD = 0.1 nmi
ALIM = 340 feet

Performance Level 4: TRTHR = 25 seconds
DMOD = 0.3 nmi
ALIM = 340 feet

Performance Level 5: TRTHR = 30 seconds
DMOD = 1.0 nmi
ALIM = 440, 640, 740 feet

2. The outer limits of the range/altitude performance level boundaries selected for Houston area airports as a result of this study are as follows:

Performance Level 2: Range = 2 nmi
Altitude = 900 feet

Performance Level 3: Range = 10 nmi
Altitude = 10,000 feet

Performance Level 4: Range = beyond 10 nmi
Altitude = 10,000 feet

Performance Level 5: Altitude = above 10,000 feet

3. The performance level threshold values and boundaries selected by this study are as close to final recommendations as can be made through studies of recorded data at a single site and simulation analyses. It is recommended that operational evaluations be continued in order to confirm or alter these findings.

4. The feature that an alert be displayed for at least 5 seconds before another alert may be displayed should be changed. In situations requiring a change of alert to one of greater severity, the time-out rule can result in significant loss of separation.

5. The threshold at which an unequipped intruder is treated by the logic as being in level flight should be less than the present 1,000 fpm. Decreasing the value would allow additional warning time

against intruders with rates under 1,000 fpm and would result in increased protection. A value on the order of 800 fpm should be effective.

6. Alternatives to the range/altitude method of sensitivity level selection should be further analyzed. Data should be made available to study the effectiveness of altitude-only desensitization as well as use of aircraft gear/flap signals to trigger performance level changes.

7. A modification should be made to the vertical divergence logic feature to prevent a positive alert from transitioning to a negative alert prematurely. This deficiency can otherwise contribute to poor separation results.

8. Consideration should be given to decreasing the threshold value at which a DESCEND alert is converted to a DON'T CLIMB from 1,000 feet to 500 feet above the ground.

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1. INTRODUCTION

The Active Beacon Collision Avoidance System (BCAS) is an airborne system which performs a surveillance function, a threat detection and threat resolution function and ultimately, a resolution display function in order to avert hazardous flight paths between threatening aircraft. BCAS makes use of surveillance data to determine the positions of other aircraft in its vicinity. BCAS determines when other aircraft are threatening and what actions can be taken to provide safe separation. The Active BCAS logic is capable of coordinating resolution actions with other BCAS equipped aircraft.

Since its inception, the BCAS logic was designed to provide multiple levels of protection. The threat detection and resolution decisions make use of thresholds which shape varied protection volumes around an equipped aircraft. The logic detection parameters are defined by the performance level in which the logic is operating in any given airspace. In order to maintain safe and effective system operation, the performance levels increase or reduce detection thresholds as a function of such factors as traffic density and allowable airspeeds. Performance level selection can be made by the pilot, automatically from the ground, or automatically by the BCAS unit onboard an aircraft. Prior to this study, specific boundaries for each performance level region had not been analyzed.

Throughout the design and development stages of the Active Beacon Collision Avoidance System (BCAS) logic, measures have been continuously taken to ensure the effectiveness and efficiency of system performance. A determining factor in evaluating the performance of a collision avoidance logic is the validity of its alerts. While it is undesirable to provide ineffective protection in a true conflict scenario, it is also undesirable for a system to alert frequently in routine and safe situations. The threat detection design is a tradeoff between protection and unwanted alerts. The objective of this study is to determine how that tradeoff can be optimally made. The primary concern is the terminal area, where the problem of unnecessary alerts is the greatest.

In the past, the primary method of evaluation for collision avoidance systems has been simulation studies, through the use of diverse sets of collision and safe passage scenarios. This study, a follow-on to the Interim Houston Data Analysis (Reference 1), has made use of over 65 hours of real world data

in conjunction with simulation data to provide an in-depth evaluation of BCAS parameter values and performance level regions.

1.1 Previous Studies

As flight testing could not feasibly provide sufficient data nor accurate separation measurements, fast-time and real-time simulations have been the primary tool used for collision avoidance analyses. In the fast-time simulation, scenarios based on actual midair collision data and specific problem scenarios have been used to test various logic features and to measure protection. One mode of fast-time simulation, the Monte Carlo mode, is run with variations in parameters to model transponder and altimetry errors, and pilot response times. The simulation utilizes the complete Active BCAS logic for conflict detection and resolution. Results of a study conducted with this mode of simulation are reported in Reference 2. The deterministic mode is another mode of fast-time simulation. Either than randomly varying the simulation parameters, the deterministic mode uses fixed parameters and error free range and altitude measurements. Using this method, individual parameter comparisons can be made in a controlled environment.

1.1.1 Chicago and Knoxville Simulations

The second method, real-time simulation, has been used in studies conducted at the Federal Aviation Administration Technical Center. These studies performed in the Air Traffic Control Simulation Facility (ATCSF) have utilized a human interaction capability in an error free environment. One simulation was modeled after the Chicago O'Hare terminal environment and included an Air Traffic Control (ATC) simulation capability. Chicago was selected both for its high operations rates and the availability of Automated Radar Tracking System (ARTS III). A second simulation was configured after the Knoxville terminal area. Knoxville was selected for its moderate operations rates and because the ARTS III system is not available. In both simulations, standard clearances given by air traffic controllers were sent to operators, acting as pilots, to be keyed into the computer. The computer simulated the appropriate response and controlled aircraft flight paths. Commands generated from the BCAS detection and resolution logic were displayed to simulated pilots and, via computer, responses were modeled. Air traffic controllers were not directly informed of BCAS messages. They were only aware of BCAS advisories when they noticed the aircraft deviating from their assignments. Results of these studies are reported in References 3 and 4.

While these simulations have proven invaluable in determining the impact of BCAS on air traffic controllers and control procedures, they were not based on actual real-world data. Real-world data provides a more viable tool for evaluating BCAS performance than most simulations. This is so because visual separation mechanisms and near-airport runway interaction effects cannot be readily accounted for in these simulations.

1.1.2 Jolitz Study

The first study which made use of real-world data was conducted for the Airborne Collision Avoidance System (ACAS) using data recorded at ARTS III radar facilities (see Reference 5.) This study, conducted by G. Jolitz, included 48 one-hour data samples from Washington National, Chicago, Los Angeles, and Miami Airports. Alarm rate statistics were analyzed before and after the application of a single desensitization area which switched the ACAS to landing mode. In the landing mode, in which smaller protection volumes were applied, the number of alerts decreased. No parametric sensitivity analyses were performed in the Jolitz study. Rather, emphasis was placed on studying the response of the ACAS to varying ATC environments. Results of the analysis concluded that desensitization near airports would be required and that the desensitization would be airport dependent.

1.1.3 Preliminary Evaluation of Active BCAS Performance (Simulated)

Reference 2 quantified for the first time the performance trade-off between alert rates and protection. The alert rates were based on ARTS data from Washington, D.C. and Philadelphia terminal areas. The data consisted of six one-hour recorded segments. The protection measures were made through both Monte Carlo and deterministic simulations of a diverse set of collision scenarios.

This evaluation concluded that a TRTHR of 25 seconds and DMOD of 0.3 nmi provided an acceptable compromise between unnecessary alerts and protection for the data set studied. (Specific parameter values will be discussed in Section 3.)

1.1.4 Interim Houston Analysis

In 1979, a study was performed by MITRE on 65 hours of ARTS III radar data collected at Houston Intercontinental Airport. See Reference 1. The interim Houston analysis provided the impetus for this current in-depth study by verifying the need to adjust

those conservative parameters which generated an unacceptable number of unnecessary alerts. Recommendations resulting from the interim study were that a follow-on analysis be conducted to determine optimum BCAS desensitization values and regions. It was suggested that sensitivity studies be performed for each critical BCAS parameter to determine which parameters provide the best tradeoff between alert rate and safety. In particular, the high alert rate near airports was singled out as an area needing close attention.

1.1.5 Follow-On Houston Analysis

There are several important differences which make the Houston studies unique and justify the additional analysis of ARTS extractor data beyond that performed in the Jolitz study.

- The Houston studies include all Mode C aircraft seen by the radar rather than controlled aircraft only. This has proven to be a significant factor in the analysis of alert rates.

- The studies contribute to our understanding of Active BCAS by presenting alert rates in terms of per-aircraft rather than per-airport rates.

- The data used in the Houston studies has been reduced and stored in an easily accessible manner for repeated use. Parameter and logic variations can be tested and verified in this way.

- This current study has performed extensive parameter and boundary analyses looking at many individual encounters to determine which should and which should not be eliminated in order to quantify the effects of desensitization on alert rates.

- The current study has analyzed the tradeoffs not solely on the basis of alerts, but taking into account the loss of protection given up through desensitization.

1.2 Methodology

The BCAS desensitization study was conducted in two parts. The first consisted of running the BCAS logic, with several sets of selected parameter variations, against the Houston ARTS data base. The alert data was then filtered by altitude and range from the airports in order to determine suitable performance

level mappings. Calcomp plots, showing the location of all alert pairs, were used for alert rate and distribution comparisons. In addition, individual aircraft encounters were analyzed extensively to study specific problem areas and distinguish justified alerts from unnecessary ones.

Once tentative parameter values and performance level regions had been identified from this first step, a second analysis was begun to verify separation protection with the new parameters and identify any tradeoffs. This analysis utilized Monte Carlo fast-time simulations of actual midair collision situations. Fifteen midair scenarios provided the basis for point-to-point simulation of one-on-one encounters. Variations were applied to escape rates, acceleration rate, pilot maneuver delay, and initial position, velocity, and altitude. Tracking errors were simulated in range and altitude, and errors were simulated for altitudes reported in Mode C and range reports from intruder transponders. In addition, the effects of variations in detection parameter values were analyzed via the simulation package. Specific simulation values will be discussed in Section 8.

1.3 Objectives

The primary objective of this study was to identify the optimum parameter values and desensitization boundaries which would maximize overall BCAS effectiveness. To accomplish this goal, tradeoffs were weighed between alert rate numbers and timeliness of the alerts. While reduced alert thresholds eliminate unnecessary alerts, they may fail to resolve a dangerous encounter by precariously limiting pilot warning time. The compromise between unnecessary alerts and late or suppressed alerts is a difficult one.

Another tradeoff which had to be weighed was between the extent of BCAS coverage and the inclusion of air traffic under the control of a local controller. The closer to an airport that BCAS is allowed to provide protection, the smaller the risk of midair collisions such as those which occurred at San Diego and St. Louis. The San Diego collision on 25 September, 1978 occurred approximately 3 nmi northeast of Lindburgh Field. The St. Louis midair of 27 March, 1968 occurred about 1.5 nmi north of Lambert Field. Both accidents occurred while at least one of the pilots was under the control of the air traffic controller in the tower. In maximizing BCAS coverage, consideration must be given to the significant increase in the number of unnecessary alerts related to traffic patterns. These alerts

are not simply a nuisance, but may have an additional detrimental effect on the pilot. An alert occurring at a critical moment, particularly during take off or landing, could become a safety hazard by distracting the pilot from the task at hand.

The emphasis of this desensitization study was on minimizing three major classes of unnecessary alerts: those which occur during take off or landing operations; those which correspond to traffic conducting routine operations in the pattern area; and those en route alerts which in the normal course of events result in large miss distances.

2. HOUSTON DATA

The primary source of data for the first part of this study consisted of ARTS III extractor tapes recorded at Houston Intercontinental Airport. The Houston data was selected for this study because of its availability. Houston had previously been chosen as the site for initial testing and implementation of the Terminal Conflict Alert System. It was determined that Conflict Alert could be more easily implemented in a single beacon ARTS site such as Houston than at a dual beacon site. Also, while Houston is a major airport, it has a moderate annual operations rate. It also has one of the few area support facilities capable of continuous data recording.

Twenty tapes were selected for reduction and processing, ten of which were recorded before the initiation of Conflict Alert (in October 1977) and ten of which were recorded after Conflict Alert became operational (in February/March 1978). The tapes total 65.02 hours of data. Table 2-1 provides statistical information on the Houston data. The date and starting time for each tape are presented in local standard time using a twenty-four hour clock. Weather conditions are specified separately for each tape. A classification of Instrument Meteorological Conditions (IMC) denotes that horizontal visibility was less than 3 nmi or the reported ceiling was less than 1000 feet. All other weather conditions are classified Visual Meteorological Conditions (VMC).

The weighted average count of ATC-code aircraft present at an instant in time was calculated to be 21.3 while the average for 1200-code aircraft was only 3.2. The average count for each tape was weighted according to tape duration. (The term, code, means the Air Traffic Control Radar Beacon (ATCRBS) transponder Mode 3A code. Aircraft not under the control of the ATC system reply with code 1200. Aircraft replying with any other code are assumed to be under the control of the ATC system and are referred to as ATC-code aircraft.) These numbers become significant in computing the per-aircraft alert rates which appear in Section 6.

The software that performed the initial reduction of the data counted the number of arrivals and departures at Houston Intercontinental Airport for each tape. An established track which initially was outside a cylinder centered on the airport with radius 4 nmi and height 3000 feet, and which later was inside the cylinder was considered an arrival. A track which initially was within the cylinder and later was outside was

TABLE 2-1

CHARACTERISTICS OF THE HOUSTON DATA AT THE THREE AREA AIRPORTS

TAPE ID	DATE	START TIME LST	DURATION HOURS	WEATHER	NO OF ARRIVALS	NO OF DEPARTURES	ARR & DEP PER HOUR	AVG NO OF ATC CODES	AVG NO OF 1200 CODES
9B	10-24-77	0920	3.74	IMC	62	74	36.4	16	0
12B	10-25-77	0610	4.08	IMC	33	53	21.1	16	0
13B	10-25-77	1018	2.69	VMC	54	41	35.3	21	1
14B	10-25-77	1306	3.11	VMC	73	66	44.7	20	3
17B	10-26-77	0707	2.89	IMC 0930	36	58	32.5	21	1
18B	10-26-77	1002	3.15	VMC	68	62	41.3	20	5
19B	10-26-77	1316	2.80	VMC	72	59	46.8	21	7
24B	10-27-77	0849	3.49	VMC	57	57	32.7	19	4
25B	10-27-77	1225	2.05	VMC	43	38	39.5	22	5
33B	10-29-77	1327	4.54	VMC	83	69	33.5	14	5
1A	2-28-78	0653	4.47	IMC 1030	54	85	31.1	20	0
3A	2-28-78	1540	2.32	VMC	65	55	51.7	24	5
5A	3-01-78	0629	3.61	VMC	54	75	35.7	21	1
6A	3-01-78	1007	3.13	VMC	58	52	35.1	25	2
7A	3-01-78	1329	2.40	VMC	56	66	50.8	25	2
12A	3-02-78	1045	3.98	VMC	87	81	42.2	23	0
17A	3-03-78	1054	3.33	VMC 1254	62	87	44.7	28	1
18A	3-03-78	1415	2.59	IMC	61	80	54.4	33	1
19A	3-03-78	1700	2.68	VMC	69	66	50.4	29	1
25A	3-05-78	1205	3.97	VMC	78	84	40.8	19	5

TOTAL DURATION OF SAMPLE = 65.02 HOURS
WEIGHTED AVERAGE NO. OF ATC CODE AIRCRAFT = 21.3
WEIGHTED AVERAGE NO. OF 1200 CODE AIRCRAFT = 3.2

ACTIVITY STATISTICS APPLY ONLY TO AIRCRAFT REPORTING ALTITUDES (MODE C EQUIPPED)

counted as a departure. To indicate the level of activity at the time of the tape, the average number of arrivals plus departures per hour is given. For the most part, tapes recorded during peak hours were selected for the study.

The software then performed the reduction and recorded the average number of established tracks. This data is presented in the table separately for aircraft squawking the Mode A code of 1200 and for those aircraft squawking an ATC-code. Only aircraft reporting Mode C data contribute to these averages.

2.1 Houston Environment

In analyzing the Houston data, it is essential to note a few significant factors in the Houston airport environment. Figure 2-1 depicts the physical relationships which exist among the three airports included in this study.

Houston Intercontinental Airport, the largest, has a tower, a Group II Terminal Control Area (TCA), and parallel as well as non-parallel runways. There are two sets of parallel runways, each of which consists of one major long runway and a short parallel runway used for short takeoff and landing aircraft. Houston handles the majority of air carrier operations in the area. Hobby Airport is a large general aviation airport about 20 miles south of Houston. Having once acted as the commercial airport prior to the opening of Houston Intercontinental, it also contains a control tower and the capability of handling a high density of traffic. As can be seen in Figure 2-1, the Houston TCA has been intentionally distorted to allow general aviation aircraft free access to Hobby. The third airport in the Houston environment is Ellington Air Force Base. Military traffic is handled at Ellington.

2.2 Data Reduction

The data reduction process, which was performed for an earlier study of Conflict Alert, is described here for background information. First, the beacon radar interrogates all transponder equipped aircraft within radar range. The radar has a beam that sweeps 360 degrees (every 4.7 seconds) around the radar site. In each radar scan, the ARTS extractor is capable of recording any of several coded messages from the ARTS computer. This analysis uses only the sector time and target report messages. The sector time gives the time in seconds. The target reports include the aircraft's slant range, azimuth, Mode A beacon code, and depending on aircraft equipage, Mode C altitude replies. The slant range, azimuth, and altitude are

HOUSTON TCA

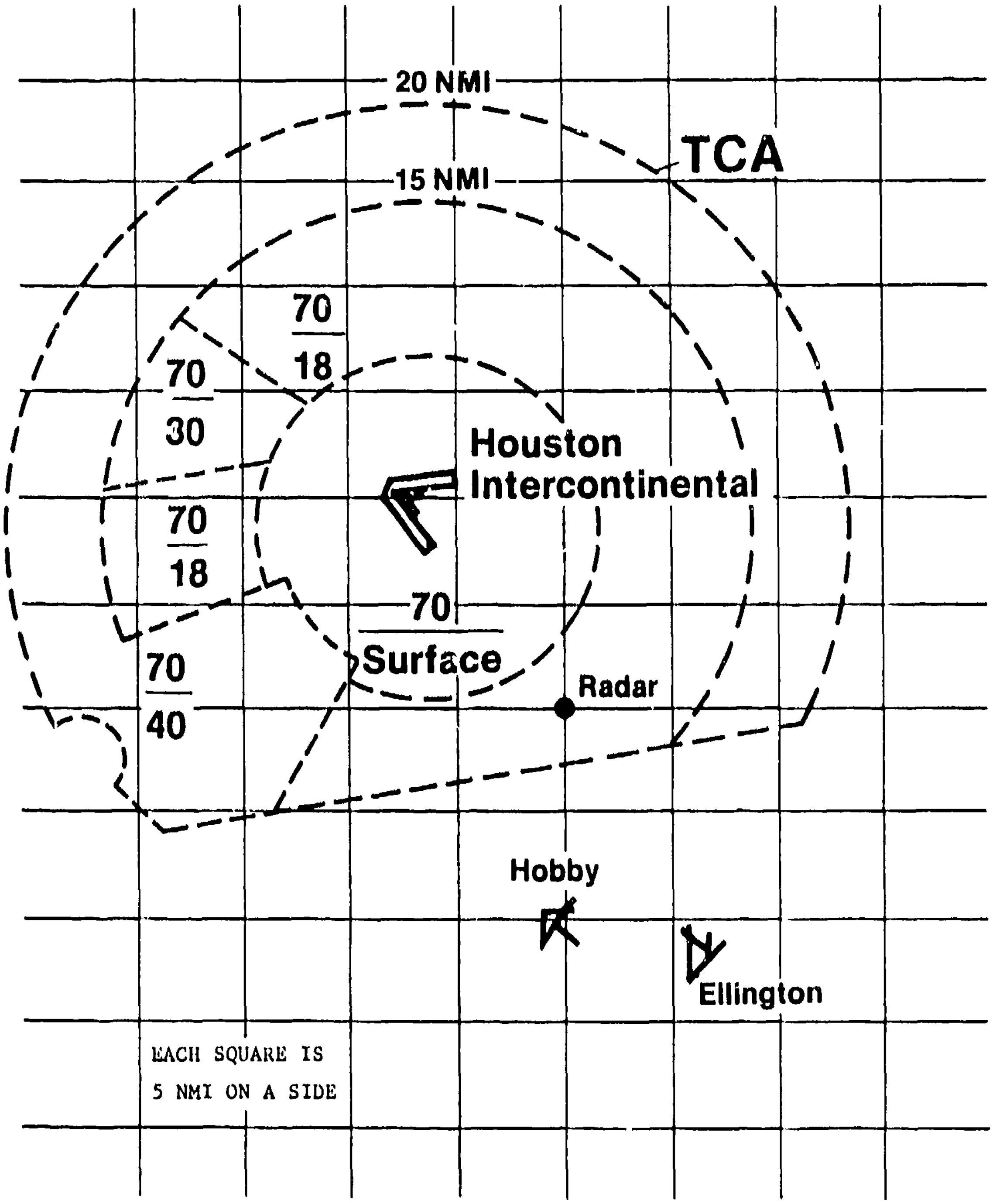


FIGURE 2-1
THE HOUSTON TERMINAL ENVIRONMENT

converted to x, y, and z coordinates. Since altitude information is necessary for BCAS conflict detection and resolution, only those aircraft with Mode C (altitude reporting) transponders were considered for this investigation. The ARTS facility performs tracking of only controlled aircraft. In the BCAS desensitization analysis, there is an interest in both controlled aircraft (those in contact with a controller and flying according to Instrument Flight Rules (IFR)) and uncontrolled aircraft (those not in contact with a controller and flying according to Visual Flight Rules (VFR)). Therefore, the ARTS tracking feature was not used. Rather, tracks were created from the target reports in the ARTS extractor output.

During the earlier study of Conflict Alert, three stages of data reduction were performed on the raw ARTS extractor data using software developed at The MITRE Corporation. The first stage of the data reduction involved reading the target reports of interest from the extractor tape and converting them to x, y, and z coordinates.

The second stage was the correlation of the data into tracks. The data points themselves were not changed, but were organized into a time ordered track. This was more complicated in the VFR aircraft case. These uncontrolled aircraft had no unique beacon codes but all had codes of '1200'. It was difficult to arrange this '1200' data into tracks. Once correlated, each '1200' track was given an alphanumeric suffix to distinguish it from other tracks. Some errors in the correlated reports have been discovered. In some cases, the ARTS extractor data was missing a few scans in the middle of a track. The correlation software interpreted this noncontiguous track as two different tracks. Sometimes when the correlator encountered a short gap in a track it would "coast" the data. This is to say it would fill in the gap as if the aircraft had continued at its last reported velocity. This presented difficulties, as will be evident later, in the evaluation of some encounters.

The third stage of data reduction involved tracking and smoothing, using the Automatic Traffic Advisory and Resolution Service (ATARS) tracker. ATARS is a ground based collision avoidance system which monitors aircraft via a Discrete Address Beacon System (DABS) surveillance capability. Up to this point the data contained only information on position and time. In this stage the position data was tracked to estimate aircraft velocities, and the position coordinates were smoothed. These smoothed tracks were passed into a coarse detection logic. The parameters in the logic were set to filter out only pairs of tracks that would be of no interest to a collision avoidance

logic. The pairs of tracks passing the filter were those that might cause an alert under any collision avoidance logic with reasonable parameters. The data collection and reduction was then completed with the product being tracks (positions, estimated velocities, and times) of potentially conflicting pairs of aircraft.

Figure 2-2 depicts the major function of each of the three reduction phases. More explanation about the data reduction process can be found in Reference 6.

2.3 Active BCAS Logic

The Active BCAS logic has been in a continual state of refinement. This is reflected in this study, through incorporation of interim logic improvements. Therefore, the logic presented in earlier sections of this document differs from that presented in the later sections. By the same token, results of flight testing could spur further refinements which affect alert rates and protection. The alert rates appearing in Section 6 of this document are the result of cumulative logic updates made throughout the course of this study. They reflect the characteristics of the Active BCAS logic existing as of the time of publication of this document.

Figures 2-3(a) through 2-3(c) are flowcharts of the detection and resolution logic used for the Houston data analysis. The code is based on BCAS collision avoidance algorithms of Reference 7. The accompanying Tables 2-2 and 2-3 define the parameters and variables used in the algorithms. The portion of the flowcharts which is marked by a rectangular dotted line is that logic which is modified in later sections. Updated flowcharts will be presented as needed. The next two sections are provided to give a high level overview of the Active BCAS logic, which appears in the flowcharts.

The Active BCAS is an onboard system that actively interrogates, in Mode C, nearby aircraft equipped with Air Traffic Control Radar Beacon System (ATCRBS) or DABS transponders and altitude encoders. The transponder replies give a direct measure of range and altitude. BCAS tracks successive replies to calculate smoothed values of range, relative altitude, range rate, and relative altitude rate (relative altitude being defined from the BCAS equipped aircraft to the responding aircraft).

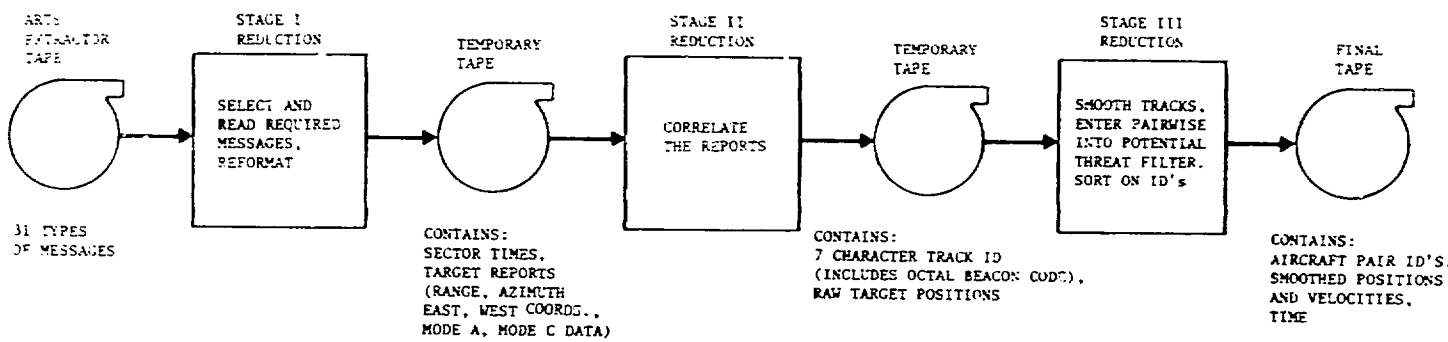


FIGURE 2-2
ARTS EXTRACTOR TAPE DATA REDUCTION PROCESS

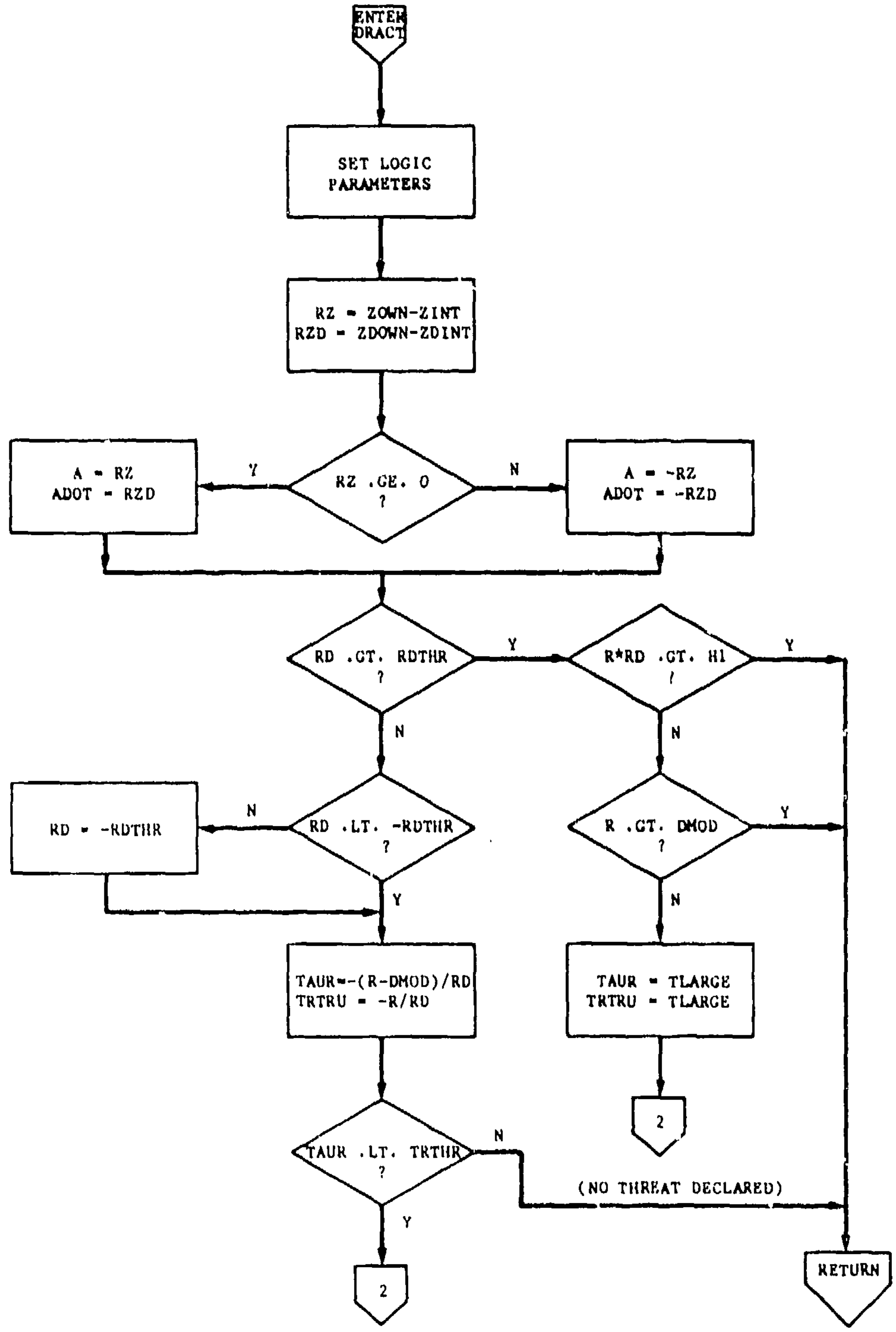


FIGURE 2-3(a)
DETECTION AND RESOLUTION (DRACT) FLOWCHART

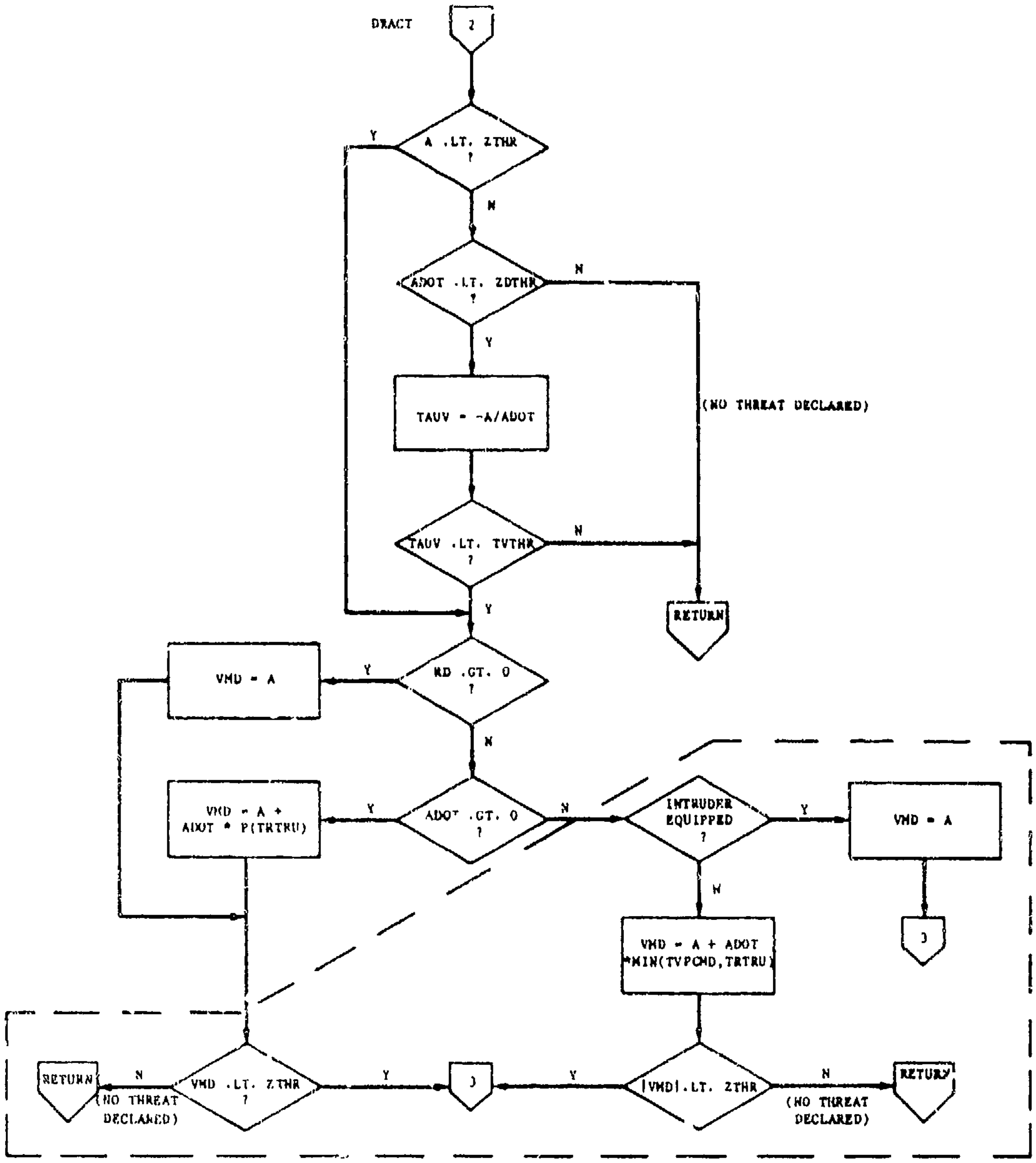


FIGURE 2-3(b)
DETECTION AND RESOLUTION (DRACT) FLOWCHART (CONTINUED)

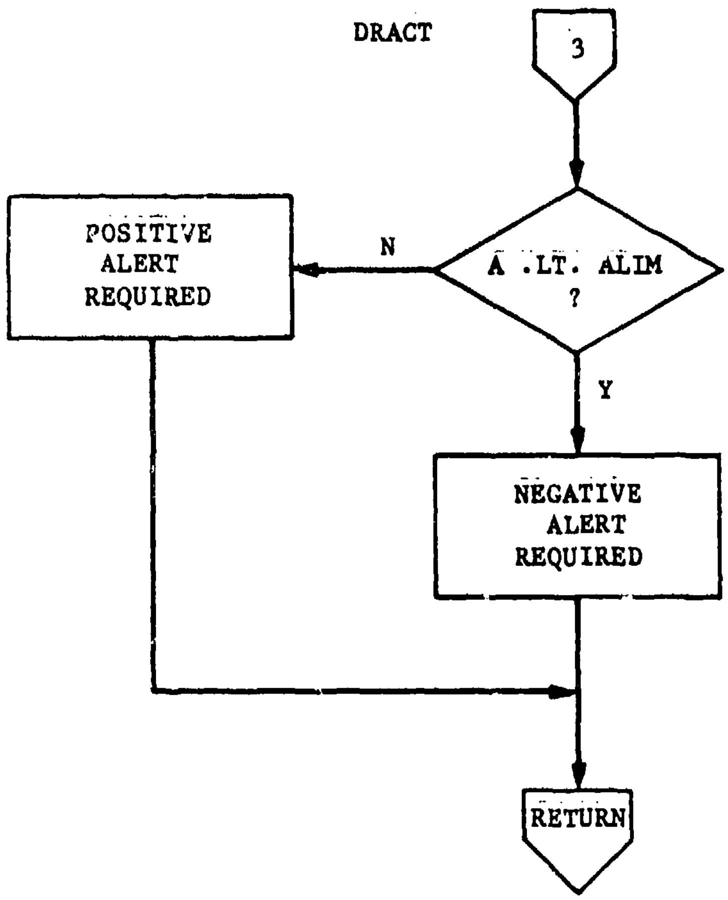


FIGURE 2-3(c)
DETECTION AND RESOLUTION (DRACT) FLOWCHART
(CONCLUDED)

TABLE 2-2

VARIABLES USED IN DRACT

R	Tracked range to intruder
RD	Tracked range rate
RZ	Relative tracked altitude
A	Absolute value of relative tracked altitude RZ
RZD	Relative tracked altitude rate
ADOT	Absolute value of relative tracked altitude rate RZD
TAUR	Modified range tau
TRTRU	True range tau (time to collision for straight flight)
TAUV	Altitude tau (time to co-altitude)
VMD	Projected vertical miss distance (current altitude for equipped intruder)

TABLE 2-3

PARAMETERS USED IN ACTIVE BCAS LOGIC

SYMBOL	DEFINITION	LEVEL	VALUE	
			EQUIPPED	UNEQUIPPED
ALIM	Altitude threshold for choice of positive or negative alert	5 4 3	TO BE DETERMINED	
DMOD	Modification distance applied to tracked range	5 4 3	TO BE DETERMINED	
H1	Divergence threshold at which commands are inhibited	ALL	.00278	.00278 nmi^2/sec
ILEV	Threshold at which an unequipped intruder is treated as being in level flight	ALL	1000 fpm	
P( )	Weights used to predict vertical miss distance when relative altitude is increasing	ALL	INDEPENDENTLY COMPUTED	
RDTHR	Range rate threshold used to compute range tau during parallel flight	ALL	.00167	.00167 nmi/sec
TLARGE	Large positive number	ALL	1000	1000
TRTHR	Threshold applied to modified range tau for threat detection	5 4 3	TO BE DETERMINED	
TVPCMD	Look-ahead time for altitude detection	5 4 3	-- -- --	25 sec 20 sec 20 sec
TVTHR	Threshold applied to altitude tau for threat detection	5 4 3	TO BE DETERMINED	
ZDTHR	Altitude rate threshold used in threat detection	5 4 3	-25 -30 -30	-25 ft/sec -30 -30
ZTHR	Immediate altitude threshold used in threat detection	5 4 3	750 750 750	750 ft 750 750

2.3.1 Threat Detection

Unlike the ATARS or more extensive forms of BCAS, Active BCAS in its present form has no access to precision bearing information, and thus cannot avoid certain types of unnecessary alerts by means of projected horizontal separation.

The range criterion for the Active BCAS logic uses a modified tau computation for aircraft closing in range. Since true tau is a linear projection of time to collision, late warnings would result for low closing rate situations. This is compensated by a distance modification (DMOD).

The altitude criterion combines an altitude tau computation, a minimum altitude threshold, and a projected vertical separation. The tau computation provides an estimate of the time to coaltitude when aircraft are closing in relative altitude. Alternatively, a current altitude threshold declares aircraft to be satisfying the altitude criteria if they are currently close in relative altitude, regardless of the relative altitude rate.

A test of a projected vertical separation, referred to as Vertical Miss Distance (VMD), and a projected range separation is made. VMD is the vertical separation at the time of smallest slant range. These tests serve to reduce the number of alerts in situations in which the horizontal and vertical closest approaches occur at different times. The VMD calculation also provides a feasible method of allowing extra lead time against unequipped intruders. The VMD is calculated differently according to the geometry of the encounter.

The BCAS logic has a 2 out of 3 sliding window logic which requires that the resolution advisory criteria be met twice in three consecutive cycles in order for an intruder to be declared a threat. Note that, due to the 4.7 second ARTS data rate available to the BCAS logic in this study, the 2 out of 3 logic was circumvented. Normally, BCAS would have the capability to update at a rate of once per second. Using a 4.7 second update would cause unacceptable delays in conflict detection if the 2 out of 3 logic were implemented.

2.3.2 Conflict Resolution

To resolve conflicts safely, and yet minimize operational disruption of air traffic, the resolution algorithm considers VMD, true tau, and own altitude rate to select the type of alert required. If an alert is required, the preferred alert is the vertical speed limit, as it allows the pilot to continue to move

toward his desired altitude. If a vertical speed limit either is not applicable or does not provide safe projected separation, a negative vertical alert (DON'T CLIMB or DON'T DESCEND) is given a second preference. This command will level the aircraft if it has a vertical rate. Another use of the negative alert is to prevent initiation of a hazardous vertical maneuver. When even the negative does not provide the desired separation of ALIM feet, a positive command (CLIMB or DESCEND) is issued. The value of ALIM is chosen so that standard 500 foot IFR-VFR vertical separation does not generate positive alerts. At higher altitudes where 500 foot separations are not assigned, larger values of ALIM are used to account for increased altimeter error.

When an intruder simultaneously satisfies both the range and altitude criteria for two out of three logic updates and is declared a threat, an alert is selected and displayed following coordination. Such a two-hit requirement protects against a single noisy measurement triggering an unnecessary alert. For the same reason, two consecutive "misses" are required for dropping an alert.

BCAS continucusly evaluates the current and projected relative positions of each intruder aircraft declared to be a threat. Each threat is considered a separate conflict. Projected aircraft positions are linear projections of current aircraft flight paths. BCAS computes the separation distances based on the current dynamics of its own flight, the equipage of the intruder aircraft, and the performance level parameters in effect. BCAS selects the maneuver which is the least disruptive to normal flight and which provides safe minimum separation for the conflict.

This study is concerned with the generation of positive alerts only. No negative or vertical speed limit (VSL) alerts have been recorded.

3. DESENSITIZATION STUDY

Throughout the process of selecting desensitized parameter values and defining performance level region boundaries, it was necessary to make compromises between the goals of maximum protection and minimum unwanted alerts. This section of the report details the stepwise approach used in the desensitization study.

3.1 Sensitivity Study

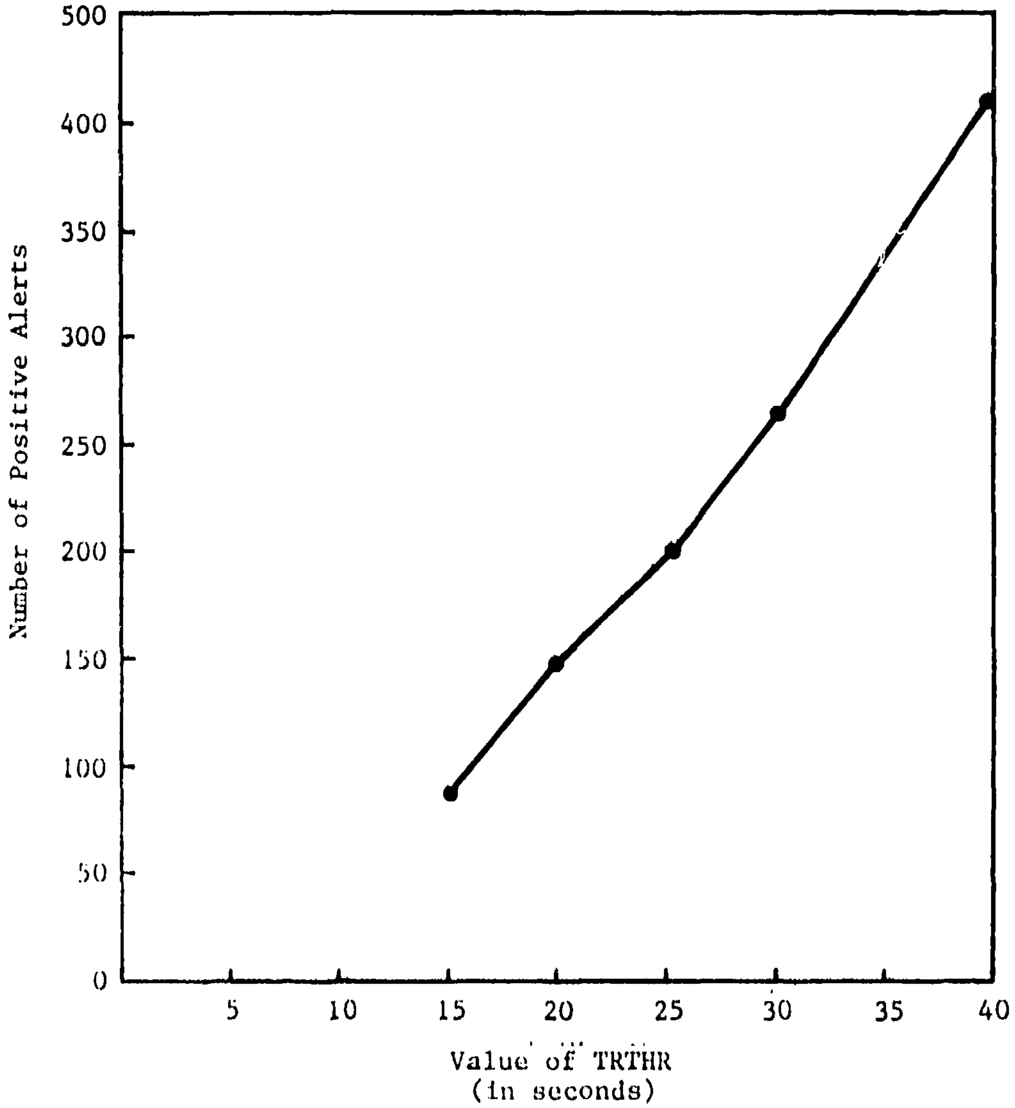
Performing parametric studies and comparing alert rates provided first results in the process of selecting desensitized values. These results came in the form of a set of alert rate numbers for which the BCAS logic could be evaluated in each performance level. The most challenging and difficult decisions had to be made by studying individual encounters to determine which alerts were unnecessary. Details of the conflict geometry analysis for these individual encounters appear in later sections.

The primary parameters identified for study were TRTHR, DMOD and ALIM (see Table 2-3 for definitions). These parameters are central to the conflict detection logic and most affect separation performance. The BCAS logic uses estimated range, R, and range-rate, RDOT, to compute a modified time-to-go (TAUR) defined by TAUR = -(R-DMOD)/RDOT. TAUR is the minimum warning time for aircraft on linear collision courses. For slow closing encounters, additional warning time is provided by the distance modifier (DMOD).

A potential conflict is detected if TAUR falls below TRTHR. A similar test is performed on vertical time-to-go (TAUV) for altitude protection. The ALIM parameter is used to determine the positive alert region. Once the range criterion has been satisfied, violation of the ALIM threshold usually results in the generation of a positive alert.

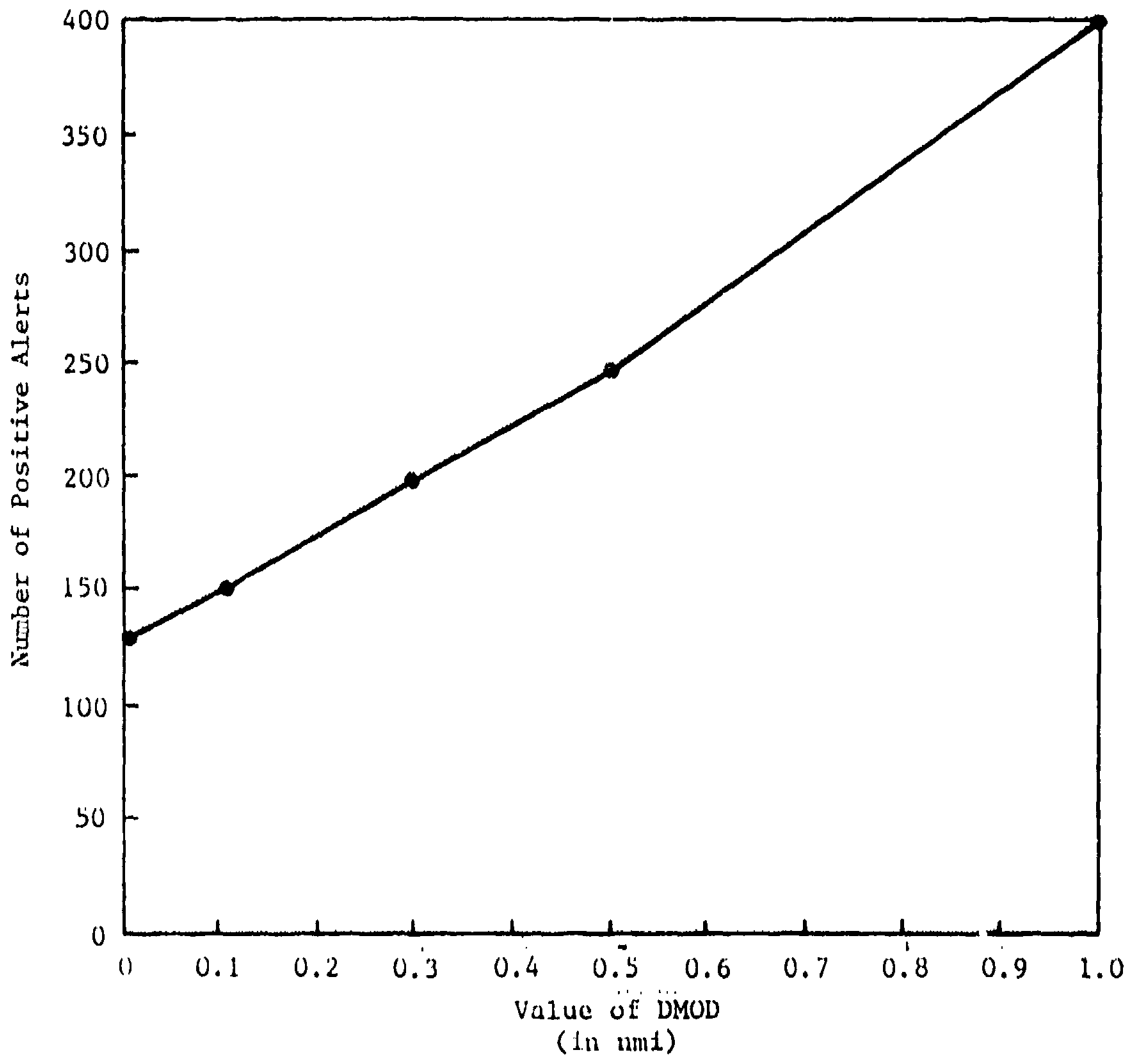
Figures 3-1 through 3-3 show alert rate sensitivity to each parameter based on the full 65 hours of Houston data. While DMOD was held at 0.3 nautical miles and ALIM remained at 470 feet, TRTHR values were systematically varied through values of 40, 30, 25 and 20 seconds. Figure 3-1 shows the result of the TRTHR variations. In the region between 25 and 20 seconds, a 31.5% reduction in positive alerts was realized.

In Figure 3-2, DMOD was varied through values of 1.0, 0.5, 0.3 and 0.1 nautical miles while TRTHR and ALIM remained at their nominal values of 25 seconds and 470 feet respectively.



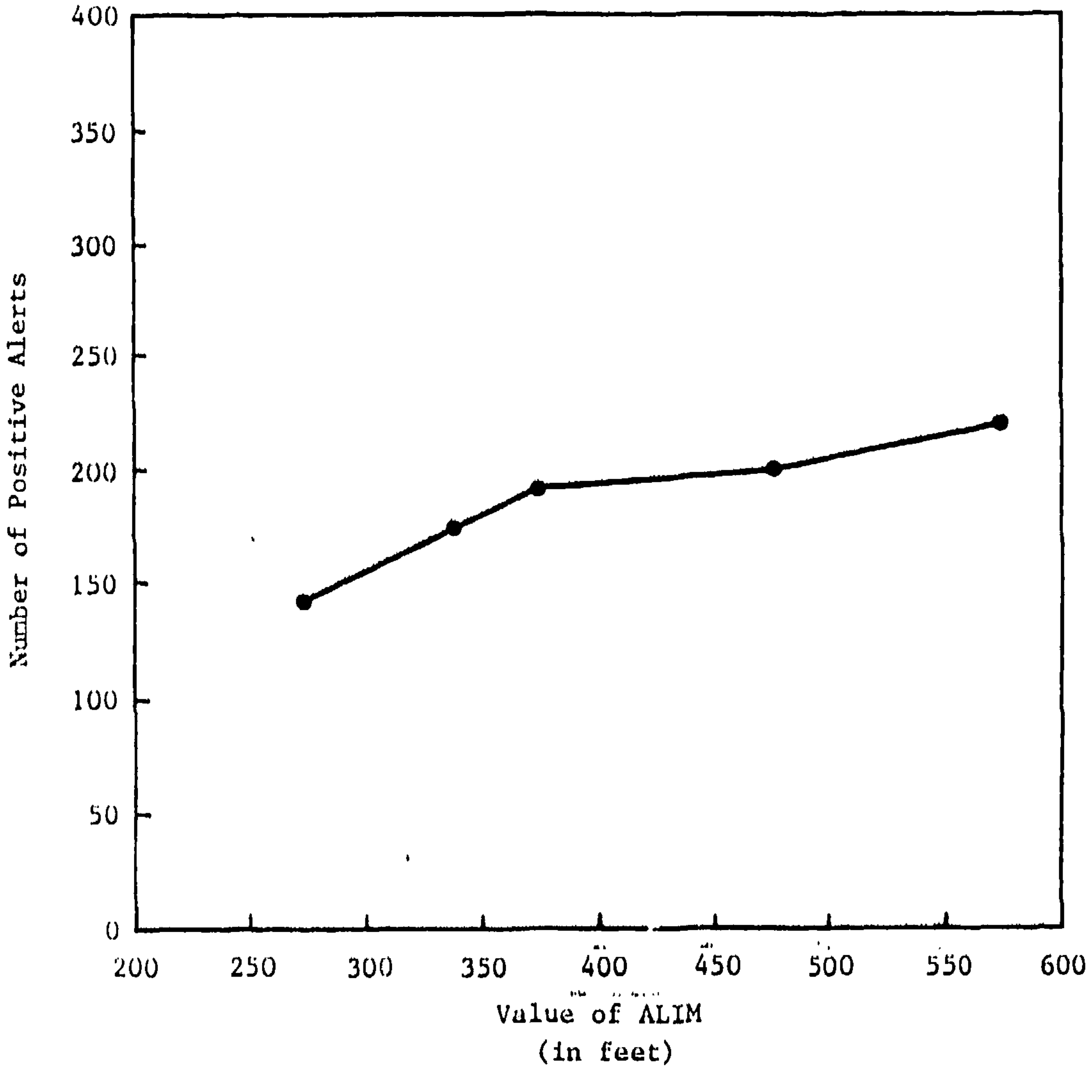
Nominal Value of DMOD = 0.3 nmi
ALIM = 470 ft

FIGURE 3-1
SENSITIVITY OF TRTHR



Nominal Value of TRTHR = 25 s
ALIM = 470 ft

FIGURE 3-2
SENSITIVITY OF DMOD



Nominal Value of TRTHR = 25 s
DMOD = 0.3 nmi

FIGURE 3-3
SENSITIVITY OF ALIM

Reducing DMOD from 0.3 to 0.1 nmi resulted in a 25% reduction in positive alerts.

Finally, ALIM was varied as 570, 470, 370 and 340 feet while TRTHR was fixed at 25 seconds and DMOD at 0.3 nmi. In Figure 3-3 the slope between 470 and 340 feet was studied. A 9.5% reduction in positive alerts resulted from decreasing ALIM from 470 to 370 feet. An additional reduction of 4.0% resulted when ALIM was decreased from 370 to 340 feet. A total reduction of 13.5% was realized from 470 to 340 feet. It is evident from these results that the value of TRTHR has the greatest impact on alert rate. DMOD and ALIM also contribute to alert rate variations, but to a lesser extent.

When an aircraft pair is in conflict the TRTHR, DMOD and ALIM parameters affect warning time. Desensitization of these conflict detection thresholds has proven to effectively reduce alert rates. The next step is to determine what, if any, tradeoffs exist with respect to decreased warning time and resultant separation. This will be discussed in Sections 4 and 8.

3.2 Analysis of Alert Rates Without Desensitization

The nominal parameter values, as defined in Reference 7, are shown in Table 3-1.

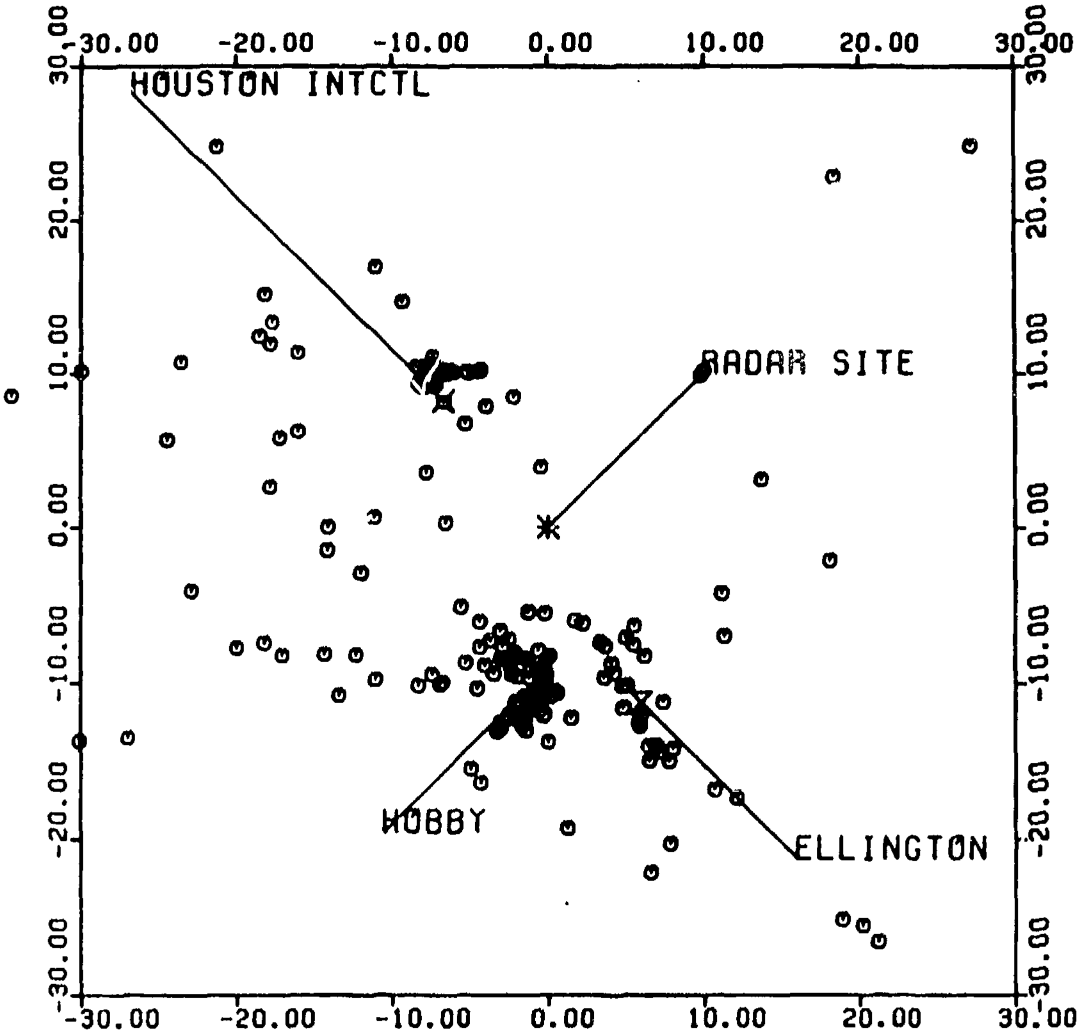
Performance level 5 provides the largest protective area. It is used at high altitudes where high speeds are allowed and altimetry errors are greater. Level 4 is an intermediate level intended for low-altitude en route airspace. Level 3 gives the smallest protective area. It is intended for terminal areas, where the need to minimize alerts is primary. Level 2 disables the BCAS logic. This level is used close to the runways, and may be selectively applied elsewhere, for example to disable BCAS within the ATARS coverage. Previously, there were no firm recommendations for where the boundaries between the performance level regions should be placed. It was one of the objectives of this study to provide such recommendations.

Using the nominal performance level 3 values of Table 3-1 at all altitudes and ranges to run the BCAS logic against the entire Houston conflict pair data base produced a total of 200 positive alerts. Figure 3-4 is a Calcomp plot of the position of the 200 alert pairs with respect to the three airports in the Houston environment. Each symbol represents the centroid of the positions of an aircraft pair in conflict at the time of the first alert.

TABLE 3-1

DETECTION PARAMETERS USED IN REFERENCE 7

	TRTHR	DMOD	ALIM
Performance Level 3	25 Sec	0.3 nmi	470 ft.
Performance Level 4	25 Sec	0.5 nmi	470 ft.
Performance Level 5	30 Sec	1.0 nmi	470 ft.



FRTHR, DMOD, ALIM PARAMETERS = 25S, 0.3 NMI, 470 FT IN ALL REGIONS
(PERFORMANCE LEVEL 3 OF REFERENCE 7)

SCALES ARE IN NAUTICAL MILES

FIGURE 3-4
DISTRIBUTION OF 200 POSITIVE ALERTS WITHOUT DESENSITIZATION

The high concentration of conflict pairs near the airports is immediately evident. Specifically, 52% of the alerts occurred within 3 nmi of an airport. This can be explained in part as a function of the traffic density in close proximity to airports. In addition, the majority of the aircraft in conflict are below 2,000 feet Mean Sea Level (MSL). (The altitude of Houston is approximately 90 feet.) This indicates that the aircraft are either landing or departing, or are in traffic pattern configurations. In many cases, while under the direction of air traffic controllers, aircraft are allowed to move into geometries which are interpreted by BCAS as potential collisions. As these situations rarely warrant an alert, it is desirable to desensitize the BCAS logic against normal pattern traffic close in to an airport.

Another cause of close-in alerts at both Hobby and Houston Intercontinental is the simultaneous use of parallel, converging, or intersecting runways. The practice of using multiple runways for various operations simultaneously is widespread. BCAS cannot be operational too near these runways. Figure 3-5 illustrates one typical conflict scenario involving two aircraft landing at Houston Intercontinental Airport on, non-parallel runways. In the plot, the tracked positions and velocities of the two aircraft as derived from the data reduction programs are shown every 4.7 seconds. The ATARS tracker, adjusted for ATCRBS data quality, was used. The data block shown at every fourth scan shows the scan number in the first field and the tracked altitude of the aircraft in hundreds of feet in the second field.

The scan numbers can be used to indicate the positions of the two aircraft at the same time. The lines drawn from the aircraft position symbols at each scan indicate the direction of the tracked velocity. The Mode A beacon code is also shown next to each track. In Figure 3-5 aircraft 4773 is last tracked at an altitude of 100 feet. Here runways 26 and 14 which are non-intersecting are being used simultaneously. In this situation, the aircraft have relatively high closing rates which lead to BCAS alerts. The aircraft are only a few hundred feet above the ground and are on short final. Alerts in these situations could be distracting to the pilots making their final approach. Also, as the aircraft are under the control and protection of the tower it would be desirable to totally inhibit the BCAS alerts at these times.

In previous studies, mention was made of the problem encountered by BCAS due to the simultaneous use of parallel runways. The Houston data, however, has shown that non-parallel runways also

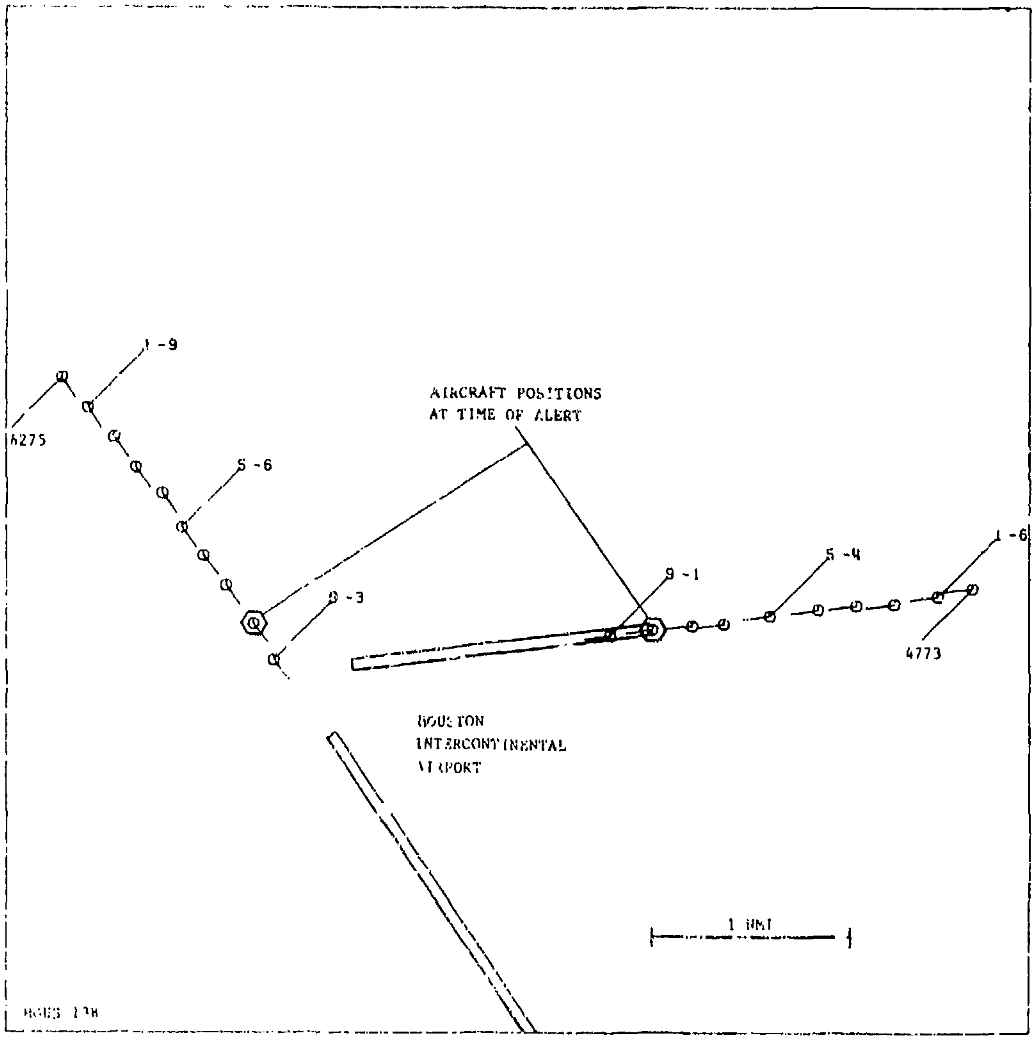


FIGURE 3-5
ALERT INVOLVING LANDING ON RUNWAYS 26 AND 14 AT HOUSTON INTERCONTINENTAL AIRPORT

present similar problems for BCAS. The configuration of runways alone does not seem to significantly affect alert rates. Strict desensitization near airports is necessary regardless of runway configuration. Section 4.6 discusses additional runway uses of particular interest to BCAS desensitization.

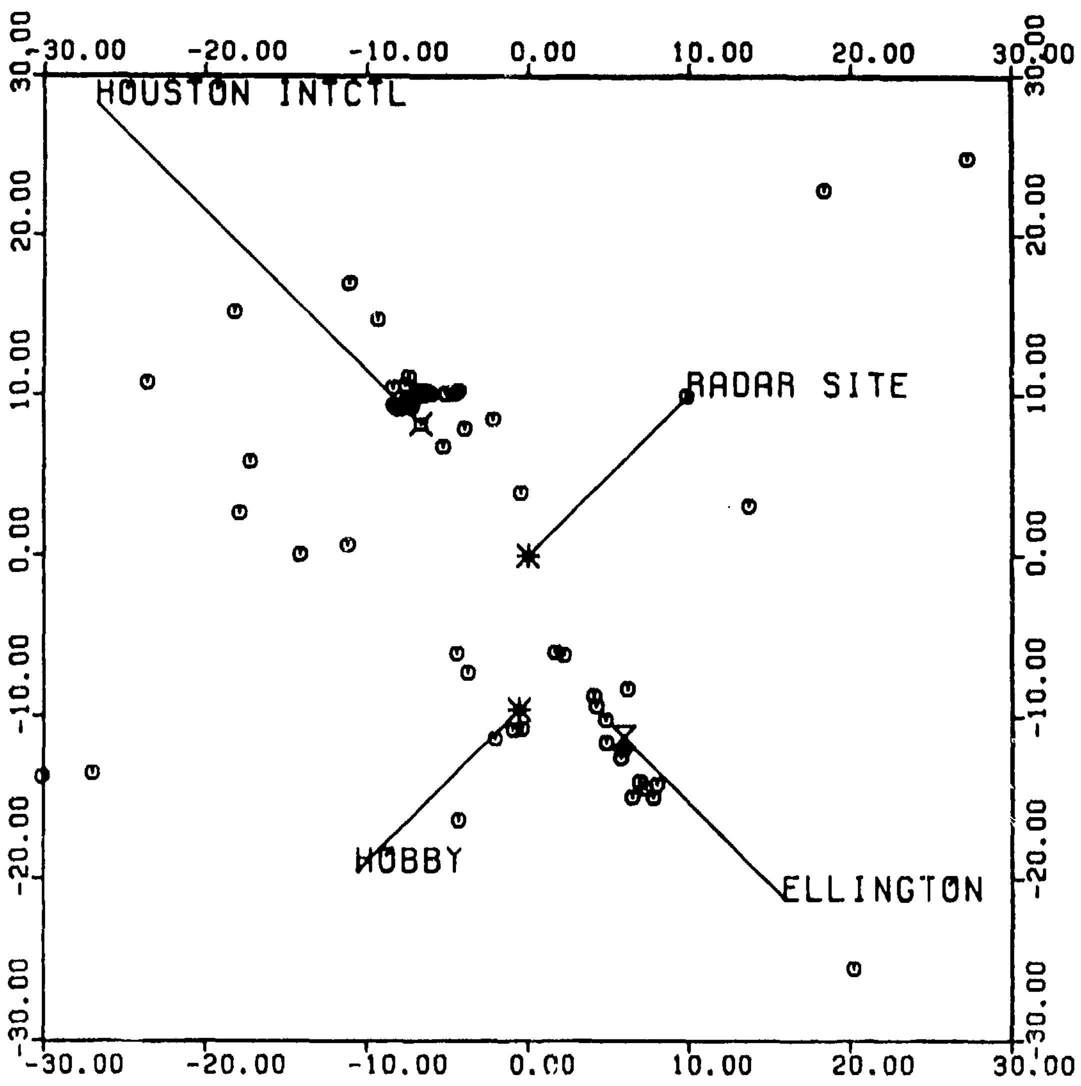
3.3 Beacon Codes of Aircraft Involved in BCAS Alerts

Figures 3-6 through 3-8 depict the breakdown of the 200 positive alerts in the Houston environment by type of beacon code. A high concentration of alerts between two ATC-code aircraft in the vicinity of Houston Intercontinental is evident in Figure 3-6. The plot also shows a significant number of ATC-code conflicts near Hobby and Ellington airports. Ellington Air Force Base presents a special case because it assigns its own codes to military aircraft in its vicinity. The ATC-code conflicts occurring near Ellington are not likely to involve air carrier aircraft. While it would have been desirable to isolate the alerts generated for air carrier aircraft, data to support this activity was not available for study. The alert rate for aircraft with ATC-codes provides the best indication of what the air carrier alert rate would be.

This study has stressed the importance of uncontrolled aircraft interaction in the data base, particularly its effect on alert rates. Figure 3-7 shows the distribution of alerts between two 1200-code aircraft. The high concentration of alerts around Hobby airport clearly depicts the role of Houston Intercontinental's distorted TCA boundary. It allows for free access to Hobby by uncontrolled aircraft.

Figure 3-8 is the distribution of mixed alerts occurring between one ATC-code and one 1200-code aircraft. There appears to have been a good mix of aircraft throughout the Houston data base. Statistics show that for those encounters in which an ATC-code aircraft was involved in a positive alert beyond 3 nmi from an airport, 41% of the cases involved a 1200-code aircraft as the second aircraft. While the ratio of average instantaneous counts of ATC-code and 1200-code aircraft was 21 to 3, the 1200-code aircraft were involved in a disproportionately large number of conflicts. It is clear that the inclusion of all Mode C aircraft in this study provided additional significant information not found in prior studies dealing only with controlled aircraft (e.g. Reference 5).

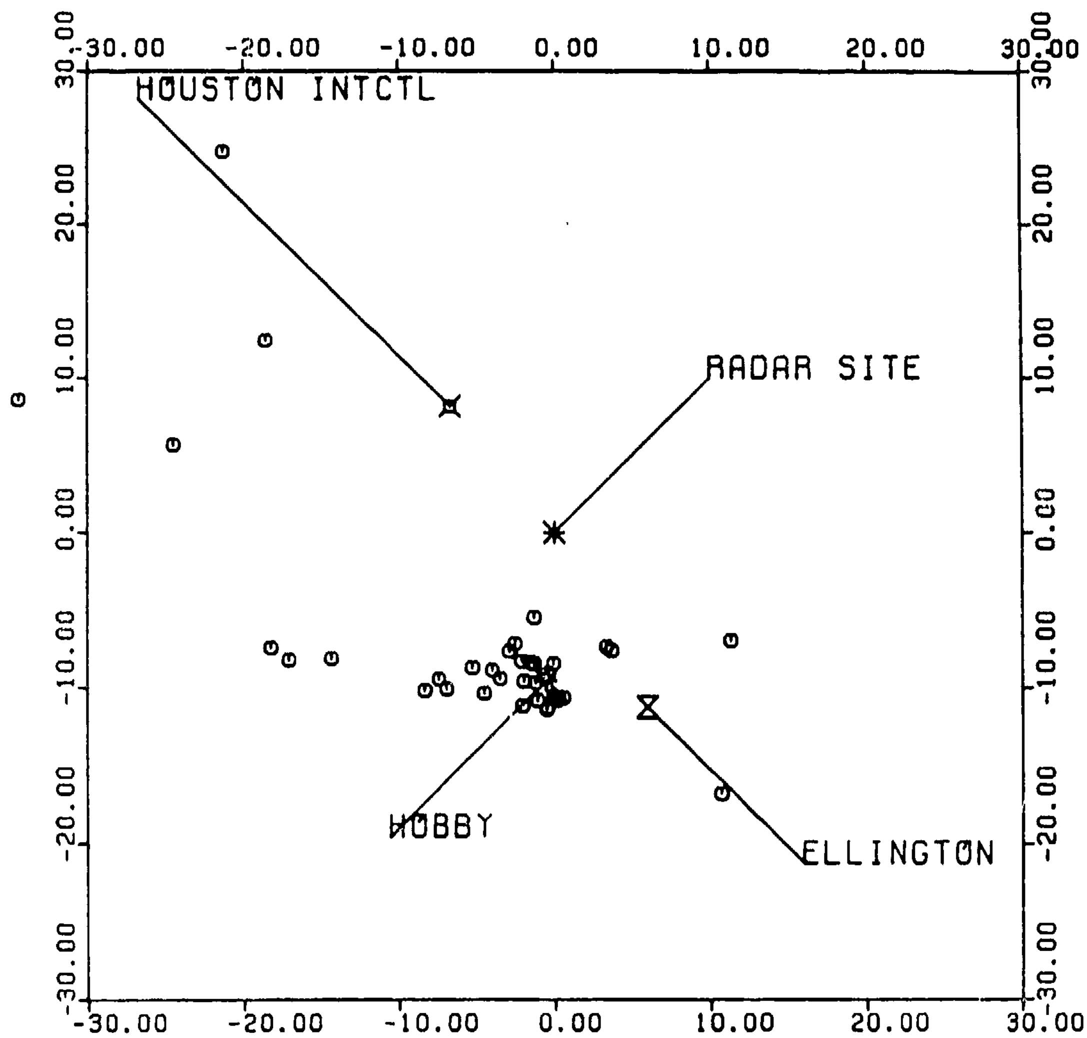
This alert distribution data confirms previous observations made about the Houston environment. Most of the alerts near Houston



TRTHR, DMOD, ALIM PARAMETERS = 25S, 0.3 NMI, 470 FT IN ALL REGIONS
(PERFORMANCE LEVEL 3 OF REFERENCE 7)

SCALES ARE IN NAUTICAL MILES

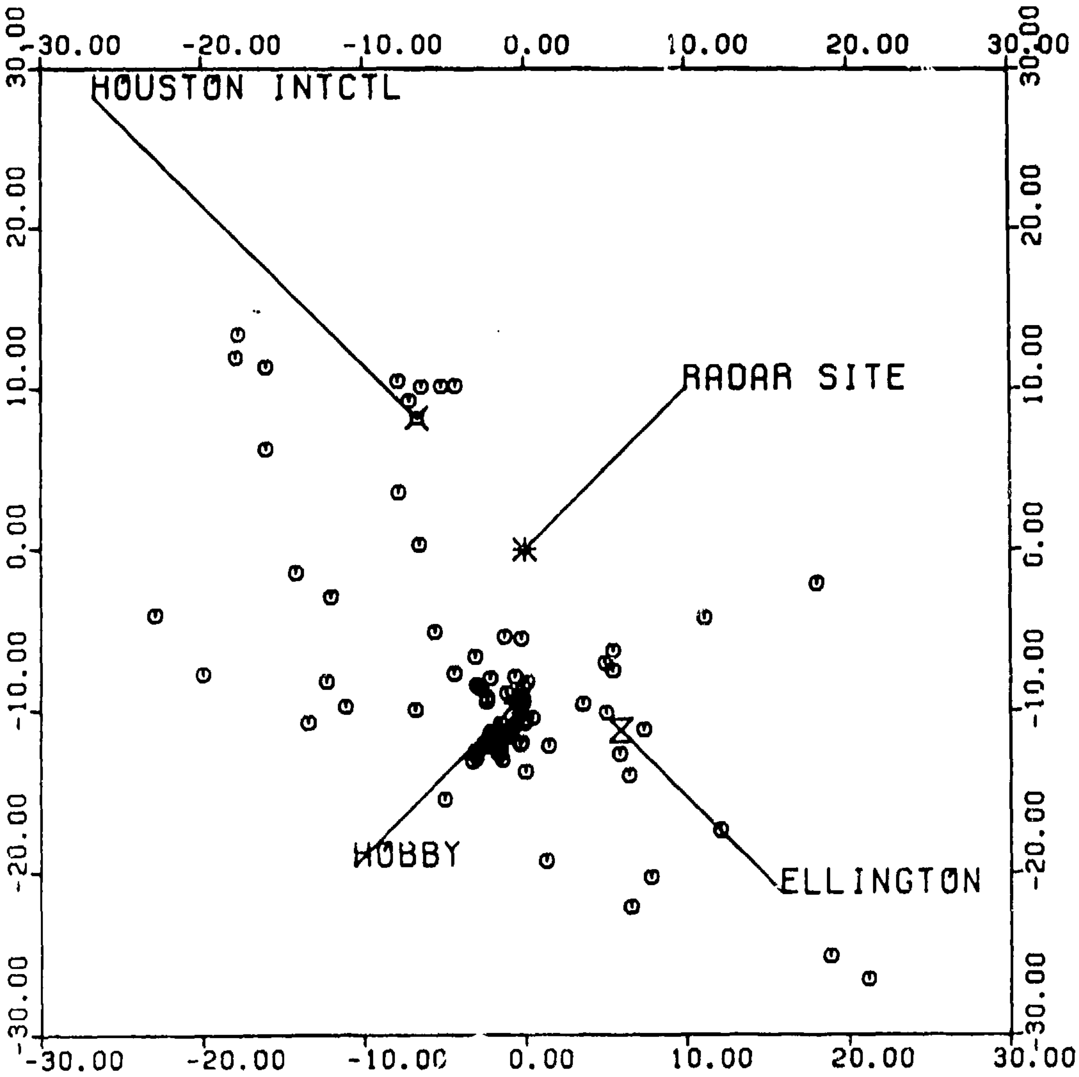
FIGURE 3-6
DISTRIBUTION OF POSITIVE ALERTS GENERATED BETWEEN TWO ATC-CODE AIRCRAFT



FRTHR, DMOD, ALIM PARAMETERS = 25S, 0.3 NMI, 470 FT IN ALL REGIONS
(PERFORMANCE LEVEL 3 OF REFERENCE 7)

SCALES ARE IN NAUTICAL MILFS

FIGURE 3-7
DISTRIBUTION OF POSITIVE ALERTS GENERATED BETWEEN TWO 1200-CODE AIRCRAFT



FRTHR, DMOD, ALIM PARAMETERS = 25S, 0.3 NMI, 470 FT IN ALL REGIONS
(PERFORMANCE LEVEL 3 OF REFERENCE 7)

SCALES ARE IN NAUTICAL MILES

FIGURE 3-8
DISTRIBUTION OF POSITIVE ALERTS GENERATED BETWEEN ONE ATC-CODE AND ONE 1200-CODE AIRCRAFT

Intercontinental involve ATC-code air carrier aircraft. The alerts at Hobby, however, are due for the most part to 1200-code traffic.

3.4 Desensitization of Performance Level 3

The desensitization process began by selecting new values of TRTHR, DMOD and ALIM to replace the conservative performance level 3 parameters given in Table 3-1. Relying on results of the sensitivity analysis, the values chosen for testing were a TRTHR of 20 seconds, DMOD of 0.1 nmi and ALIM of 340 feet.

The ALIM value was selected as a result of two separate MITRE studies, one concerned with the effects of altimetry errors and one concerned with the limitations of vertical trackers. Reference 8 analyzed tradeoffs between missed and false alerts associated with altimetry errors. The model of altimetry errors was based on limited empirical data for general aviation and air carrier aircraft and certain statistical assumptions that permitted quantitative conclusions to be drawn. If the ALIM threshold is set to a small value, aircraft could be at the same altitude while indicating a separation greater than ALIM. If the ALIM threshold were set to a large value, aircraft could appear to have a separation less than ALIM while actually having a safe separation which is consistent with normal vertical separations used in air traffic control. Reference 8 assumed that one aircraft in an encounter has altimetry errors typical of air carrier aircraft and the other has errors typical of general aviation aircraft. In establishing the value of ALIM for the BCAS logic, it was assumed that an aircraft carrying BCAS would have altimetry errors characteristic of the air carrier errors. Thus, in every conflict of concern to the BCAS logic, at least one aircraft would have the smaller altimetry error. Based on the data in Reference 8, the decision was made to give ALIM a value between 300 and 400 feet. The specific value was determined from a study of the BCAS vertical tracker.

Due to the transient performance of the vertical tracker, the step response in dropping from a reported vertical separation of 500 feet to 400 feet will result in the generation of a positive BCAS alert for certain values of ALIM. It is common at cruising altitudes for IFR and VFR aircraft to pass one another with altitude separations of 500 feet. It is also common for aircraft to be slightly off their assigned altitude. Since BCAS alerts should not interfere with normal flight operations, the selection of ALIM becomes an important function. The BCAS logic should be designed to tolerate a 100 foot deviation from the

nominal 500 feet separation. An optimum value for ALIM would be small enough to allow for tracker overshoot on a 100 foot drop from a vertical separation of 500 to 400 feet. In the same way, the ALIM value must be large enough to trigger an alert when separation drops below 400 feet.

Table 3-2 shows how the tracker responds in tracking the altitude and altitude rate of a single intruder to a 100 foot altitude drop from 4,500 to 4,400 feet. Z_R is the altitude report while Z_T is the tracked altitude. In this example, when own aircraft is at 4,000 feet, a 340 foot ALIM will tolerate an altitude drop by an intruder from 4,500 to 4,400 feet without giving a positive alert because the tracked relative altitude separation does not fall below 340 feet. However, if the BCAS aircraft were at 4,100 feet and the intruder were to drop from 4,500 to 4,400 feet, the relative altitude would fall below 340 feet on the second cycle after the 100 foot drop and a positive alert would be given. (The altitude tracker employed in this study uses Alpha=0.4, Beta=0.05. These values were selected as a result of two vertical tracker analyses, listed in References 9 and 10.)

Running the BCAS logic against the Houston data base with the new performance level 3 parameters at all ranges and altitudes resulted in the generation of 81 positive alerts, a reduction of nearly 60% from the original 200 alerts. For those alerts occurring within two nmi from an airport, a 63% reduction was realized. However, even with lowered parameter values, a concentration of alerts near the airports remained.

Simply reducing alert rates does not satisfy desensitization goals. The next step is to determine where the boundaries should be placed which separate the performance level regions. Of particular concern is the boundary within which BCAS should be disabled. Tracks which generated alerts must be examined in order to characterize individual encounters and measure tradeoffs in alert rates and safety.

3.4.1 Determining the Level 3-Level 2 Boundaries

The boundary most crucial to the desensitization effort is that which lies between performance levels 2 and 3. This boundary must provide flexibility for easy adaptation to different airports and to provide for the exclusion of most pattern related alerts.

TABLE 3-2

TRACKER RESPONSE TO 100 FOOT ALTITUDE DROP

Z_R (Feet)	Z_T (Feet)	Z_D (Ft/s)
4500	4500	-0.0
4400	4460	-5.0
4400	4430	-8.0
4400	4409	-8.9
4400	4395	-8.45
4400	4388	-7.23
4400	4384	-5.68
4400	4384	-4.08
4400	4385	-2.61
4400	4388	-1.37
4400	4390	-0.39
4400	4393	-0.34
4400	4395	-0.85
4400	4397	-1.16
4400	4398	-1.34
4400	4399	-1.41
4400	4400	-1.41
4400	4400	-1.37
4400	4401	-1.31
4400	4401	-1.24

3.4.2 Range Selection

As an initial filtering process, alert rate numbers were computed and recorded for concentric circles around the airports having radii of 2, 3, 4 and 5 nmi. Individual conflict geometries from each group were studied. An effort was made to isolate the smallest area in which mostly traffic pattern related alerts occurred. In the 4 and 5 nmi circles around the airports, a number of non-pattern related alerts were found. For these encounters, it would benefit the pilots for BCAS to be operational, even at a desensitized level.

Figure 3-9 shows an alert occurring almost 4 miles south of Ellington AFB. This scenario seems to be a chance low-altitude encounter in which BCAS could be useful. Aircraft 1 appears not to be in a traffic pattern, but is maintaining level flight at 500 feet. At scan 11 Aircraft 1 initiates a turn. Aircraft 2 is descending until scan 11, when it begins turning toward Aircraft 1. It is possible that Aircraft 2 is in a visual pattern to land on the major North/South runway. (The last two scans of data on the trajectory for Aircraft 2 are coasted positions by the tracker and do not necessarily represent the position and velocity of the aircraft at that time.) A positive alert is generated at scan 13 for this scenario. At that time, the aircraft are converging in range at a crossing angle of 120 degrees. At closest approach the two aircraft pass within 1100 feet horizontally and 300 feet vertically. Scenarios such as this one show the advantages of allowing BCAS to remain enabled to protect against close-in low-altitude conflicts.

Within the 2 and 3 nmi areas around the airports, however, very few of the alerts were not directly related to arrival or departure patterns. Under these conditions, the aircraft are generally under the control of the tower and would rarely benefit from BCAS intervention. In order to bring BCAS operations as close to the airport as possible for maximum coverage, the 2 nmi range boundary around the airports was selected.

3.4.3 Altitude Selection

An altitude boundary must be selected for the performance level 2 region as well as a range boundary. An additional filtering process was initiated in order to select an optimum altitude boundary above the airport within which BCAS would be disabled. Altitude limits of 500, 900, and 1200 feet were studied in conjunction with the 2 nmi range boundary. As before,

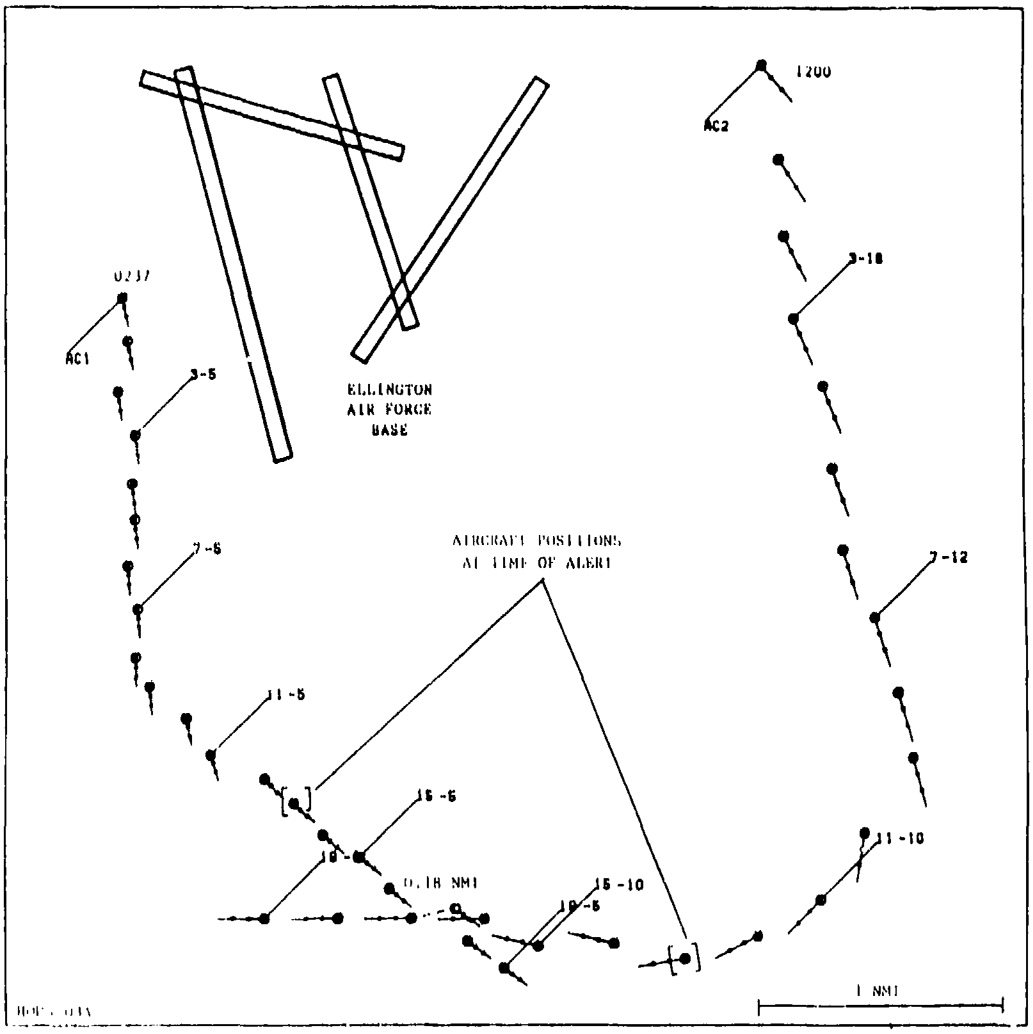


FIGURE 3-9
A LOW ALTITUDE JUSTIFIED POSITIVE ALERT BEYOND THE 2 NMI BOUNDARY

individual conflict plots provided invaluable comparison data for boundary selection. Conflict encounters occurring inside 2 nmi and between altitude boundaries were examined to determine whether or not they were due to normal traffic patterns or were essentially random encounters involving small separations.

It was judged that setting the altitude limit at 500 feet allowed the generation of too many pattern related alerts. Figure 3-10 is one such example of a close-in pattern-related alert below 500 feet within 2 nmi of Houston Intercontinental Airport. Aircraft 2 is on final approach to runway 14. In the opposite direction, Aircraft 1 is descending from 600 to 500 feet while flying parallel to runway 14. This aircraft appears to belong to a normal traffic pattern frequently observed at Houston. Several other encounters with similar characteristics have been studied and indicate that most likely Aircraft 2 will be landing on the short runway 9S. The turn has probably begun by scan 15, but due to the close proximity to the radar and the second aircraft as well as tracker lag, the data points do not yet indicate such a maneuver. In any case, a BCAS alert in such a scenario is potentially distracting and undesirable.

In contrast, setting the altitude limit at 1200 feet reduced protection against some low-altitude non-pattern related encounters which could benefit from BCAS advisories. The 900 foot altitude boundary was found, for the three Houston airports, to optimally reduce pattern alerts while affording protection against close-in, low-altitude encounters.

Adding a 900 foot altitude ceiling to the range boundary between performance level 3 and 2 reduced the number of alerts inside 2 nmi from 25 to 4. Those four remaining alerts appear to be non-pattern related.

It is quite possible that, due to different traffic patterns and runway configurations at other airports, the altitude boundary between performance levels 3 and 2 would have to be set higher than 900 feet. Final adjustments of boundaries must be made on an individual basis. It should also be mentioned that aircraft have been observed flying directly over the airfields at pattern altitudes. Alerts between such an aircraft and another aircraft established in the pattern would be considered random events which would benefit from BCAS protection. Setting an altitude boundary over an airport at 1200 feet would eliminate such encounters from the BCAS protection area.

Another factor involved in the boundary selection process was the need to completely inhibit BCAS at some point near the

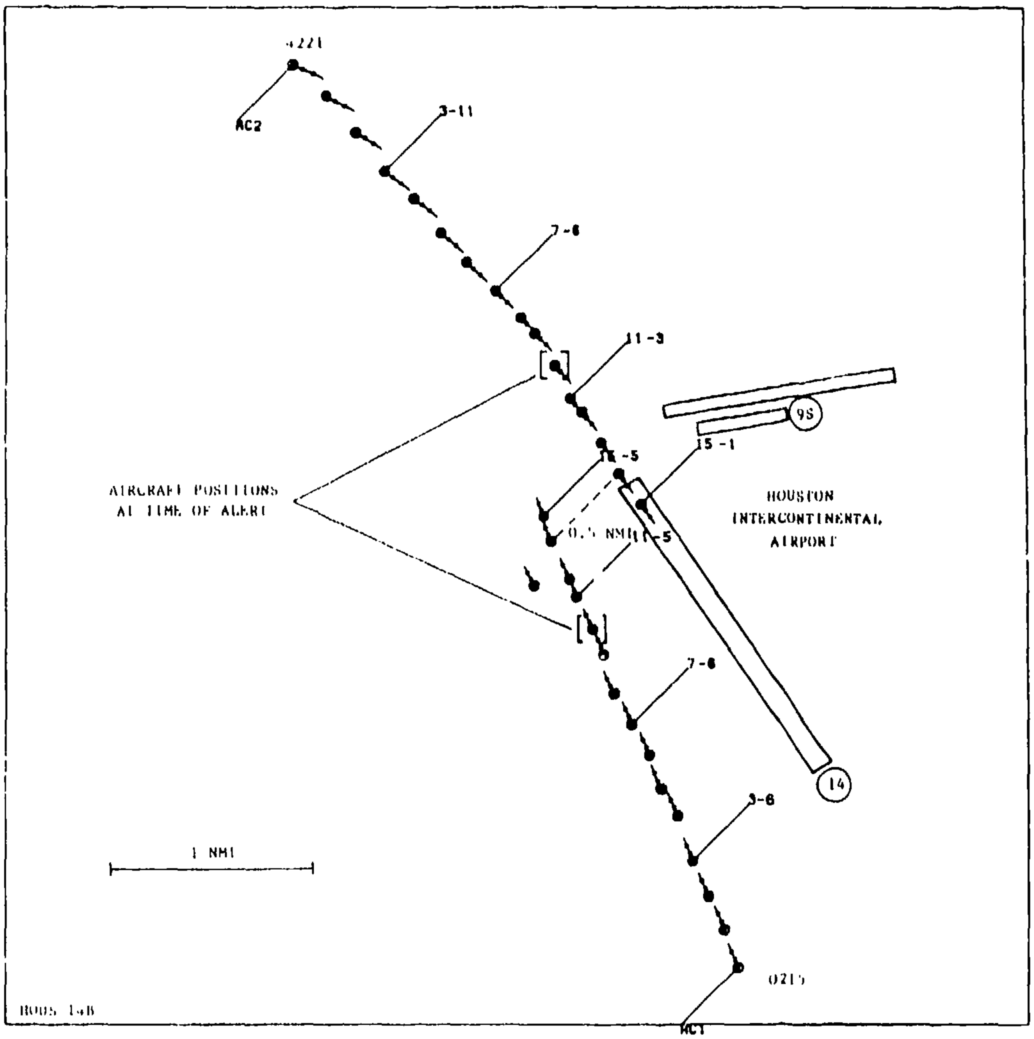


FIGURE 3-10
AN UNNECESSARY POSITIVE ALERT ELIMINATED BY THE 900 FOOT ALTITUDE BOUNDARY

runways to avoid generating alerts against aircraft on the airport surface. Because the Houston data never shows aircraft on the ground, these undesirable alerts were not evident in this study. However, preliminary flight tests have clearly indicated that such a problem exists (see Reference 11). The performance level 2 and 3 boundaries recommended in this section will effectively filter all ground aircraft from the BCAS alert display logic.

3.5 Determining the Level 3-Level 4 Boundaries

Performance level 4 parameters from Table 3-1 were desensitized in turn. The prior values of 25 seconds, 0.5 nmi, and 470 feet were replaced by the selected values of 25 second TRTHR, 0.3 nmi DMOD, and 340 feet ALIM.

3.5.1 Range Selection

The range boundary between performance levels 3 and 4 was selected somewhat arbitrarily and set at 10 nmi from the center of each airport. The number, location, and nature of the alerts did not present an obvious choice for this selection. It appears that exact placement of this boundary is not too critical.

3.5.2 Altitude Selection

The performance level 3 and 4 altitude boundary of 10,000 feet was selected by relying on existing flight procedures designated by the FAA. In addition to limiting performance level 4 to encounters occurring outside of 10 nmi from the airport, an altitude boundary was designated at 10,000 feet MSL. In this way, performance level 4 values are limited to low-altitude airspace at distances far enough from the airports to be removed from the traffic patterns. The 10,000 foot limit was selected for its role in governing allowable aircraft speed. Per Federal Aviation Regulations, aircraft which fly below 10,000 feet MSL are limited to a speed of 250 knots in both controlled and uncontrolled airspace.

3.6 Establishing The Boundaries Between Level 4 and Level 5

This study has emphasized evaluation of the BCAS logic and alert rates under the high-density, close separation conditions present in terminal areas. However, the availability of some en route data on the Houston tapes provided additional alert rate information with respect to low density areas.

Performance level 5 is used for any encounter occurring above 10,000 feet MSL. Little desensitization of this region relative to the detection parameters of Table 3-1 was done. TRTHR and DMOD remain constant throughout performance level 5 at 30 seconds and 1.0 nmi, respectively. ALIM, however, now varies according to aircraft altitude. To compensate for altimetry errors which normally increase with altitude, ALIM increases from 440 feet between 10,000 and 18,000 feet to 640 feet between Flight Level 180 and Flight Level 290 and reaches its maximum value of 740 feet for encounters above Flight Level 290.

The Flight Level 180 and 290 boundaries were selected for their significance in determining VFR and IFR flight levels for "built in" vertical separation. Regulations require aircraft flying between Flight Level 180 and 290 under visual or instrument flight rules to maintain a minimum 1,000 foot vertical separation in both controlled and uncontrolled airspace. Above Flight Level 290 the separation requirement increases to 2,000 feet. Requiring more separation compensates for the higher altimetry errors at the higher altitudes. Separation is maintained by each aircraft adhering to the even or odd flight level appropriate for its flight direction. The ALIM value is designed to increase as ATC separation standards increase. For more information, see Reference 12.

3.7 En Route Interaction

The performance level 5 region is of considerable importance when dealing with the issue of BCAS interaction with en route ATC facilities. Therefore performance level 5 data was further analyzed.

Close examination of the reduced Houston ARTS data revealed that it contains a disproportionately small number of potential conflicts above 10,000 feet. In addition, the number of potential en route conflicts, generally considered to be those above 18,000 feet was even more limited. It is important to note that the reduced data base does not contain the tracks of all aircraft seen by the radar. It contains only the tracks of those aircraft pairs potentially in conflict. Therefore, the small number of high altitude encounters found in the reduced data base signifies that few of the aircraft in the Houston en route environment ever move into conflict geometries.

Judging from this sparse number of real or potential en route conflicts, it appears that the likelihood for interaction between BCAS and en route facilities is small. It is recognized that other en route areas across the country may have a different experience.

3.8 The Role of the Radar Beacon Transponder (RBX)

The plan to equip commercial aircraft with BCAS includes certain considerations in dealing with the terminal and en route facilities. In order to ensure that the number of unnecessary alerts generated by BCAS in the terminal area does not interfere with the normal function of ATC, a desensitization mechanism must be established. In addition to desensitization, a determination must be made as to what communicati is needed between the BCAS aircraft and a terminal or en route facility. The Radar Beacon Transponder (RBX) is one means for providing automatic performance level control and ATC communication.

The RBX is a transponder with data link capability located on the ground. A BCAS aircraft tracks and interrogates ground RBXs as part of its surveillance function. Based on range and altitude information downlinked by the BCAS aircraft, the RBX selects the performance level to be used by that aircraft as long as it remains in a specified airspace region. The RBX makes the selection based on internally stored airspace region maps. These maps are designed to be airport dependent and therefore provide a great deal of flexibility in performance level control.

In addition, the RBX can be used to transmit information about BCAS generated alerts for the pilot to the ATC facility for possible display to the controller. RBXs located at various en route points could provide the same function for en route centers. Appendix A provides a discussion of the number of RBXs needed to provide performance level desensitization and the RBX site selection process.

3.9 Parameter Sets Studied

Table 3-3 enumerates the results of testing eight sets of parameter variations on the Houston data base. The progressive reduction in positive alert numbers with parameter reductions is evident at a glance. Of particular interest is the effect of reducing the TRTHR parameter by two seconds. The recommendation to use an 18 second TRTHR when both aircraft are BCAS equipped reduces the positive alert rate by 12 percent. The full impact of using two separate TRTHR values for different equipage scenarios will become evident in time. As more aircraft become equipped with BCAS and the 18 second TRTHR value takes precedence in the detection logic, the alert rate experienced by an individual BCAS-equipped aircraft will decline.

TABLE 3-3

POSITIVE ALERTS AT DIFFERENT RANGES FROM THE AIRPORT
FOR VARIOUS COMBINATIONS OF PARAMETERS

Parameter Values			Total Positive Alerts	Breakdown by Range from Closest Airport		
DMOD (nmi)	ALIM (ft)	TRTHR (s)		.LT.2 nmi	.GT.2 .LT.10 nmi	.GT.10 nmi
0.3	470	25	200	68	97	35
0.3	370	25	181	60	91	30
0.3	340	25	173	59	89	25
0.1	370	20	83	25	41	17
0.1	340	20	81	25	40	16
0.1	370	18	73	24	33	16
0.1	340	18	69	24	31	14
Selected Parameters Using 20 s for Performance Level 3			73	4	38	31
Selected Parameters Using 18 s for Performance Level 3			64	3	31	30

3.10 Alert Rate Using Desensitization

Figure 3-11 shows the final recommendations made by this study for the Active BCAS performance level regions and parameter values. Subsequent to the completion of this study, the performance level selection process emerged as a vital issue requiring precise definition and standardization. Details such as the number of performance levels, how performance levels are mapped to specific regions and the role of the RBX and other ground sites (DABS) in selecting and uplinking performance levels to BCAS aircraft have now been designed and documented. Although differences exist between the new design and that outlined in this document, it is important to stress that the basic principles remain consistent.

Using the regions and desensitized parameters shown in Figure 3-11 to drive the BCAS logic resulted in the generation of 64 positive alerts from the Houston data base. This alert rate is a reflection of the positive commands generated against equipped intruders, using a TRTHR value of 18 seconds for every level 3 conflict. The same performance level mapping scheme was used at each of the three area airports. Aircraft were assumed to be operating with the performance level associated with the mapping scheme of the nearest airport.

When an intruder is equipped, the logic takes into consideration combined coordinated escape maneuvers and higher relative escape rates. When only one of the aircraft is receiving a command, coordination of maneuvers is not possible. The decrease in separation which would result is offset by increasing TRTHR to 2C seconds against an unequipped intruder. (This stage of the study assumed BCAS equipage for all aircraft in order to obtain expedient results from the data base. It is recognized that universal equipage with BCAS is very unlikely and that a more realistic measure of BCAS performance is the alert rate assuming all intruders are unequipped with BCAS. Later sections of the study make use of the unequipped intruder logic in conjunction with BCAS logic updates.)

Comparing Figure 3-12, the Calcomp distribution plot of 64 alerts with Figure 3-4, the plot of 200 alerts, reveals a significant reduction in alert pairs, particularly in close proximity to the airports.

3.11 Altitude Only Desensitization Using the RBX

It has been suggested that simplification of the RBX method of controlling performance levels could be accomplished entirely

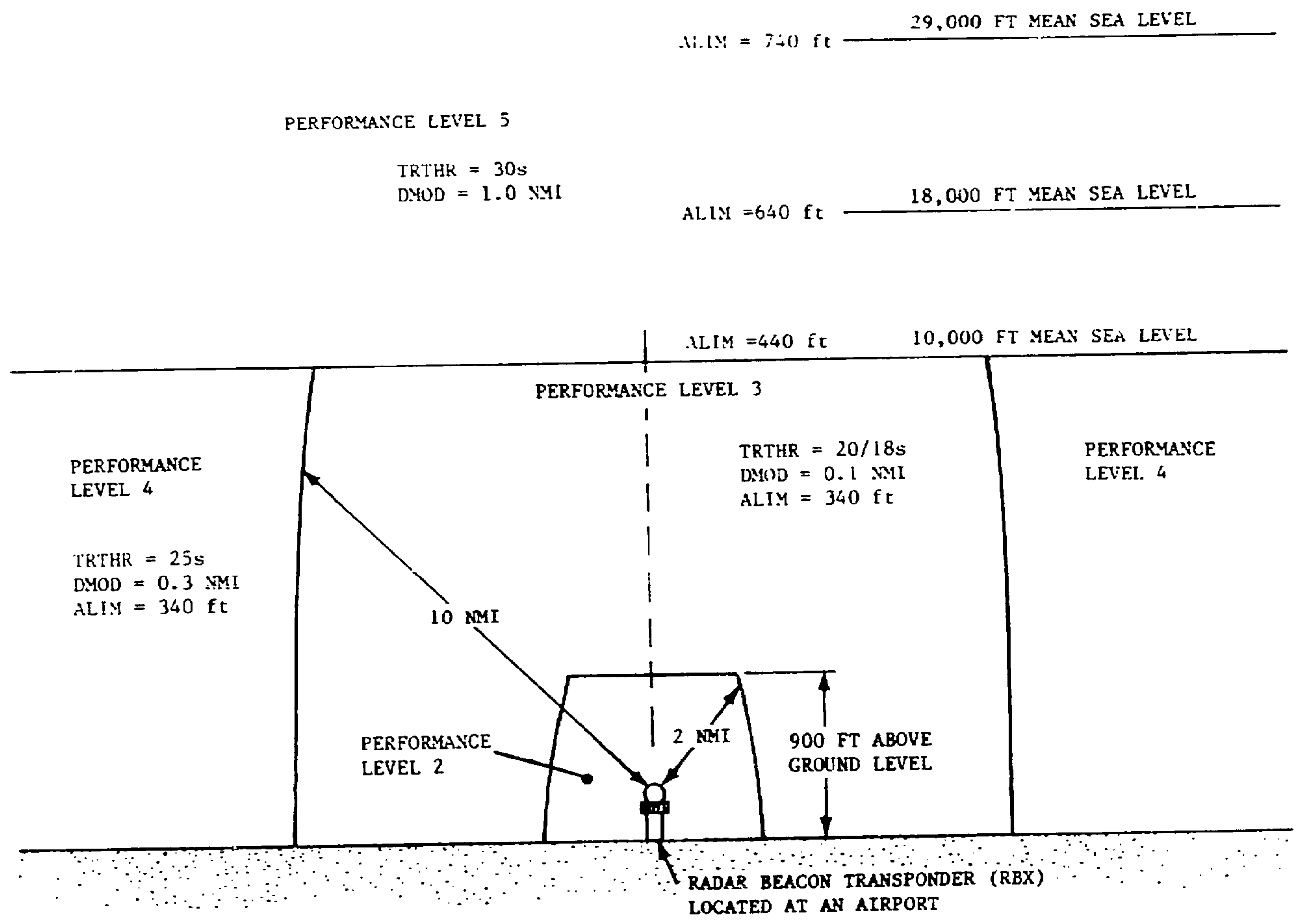
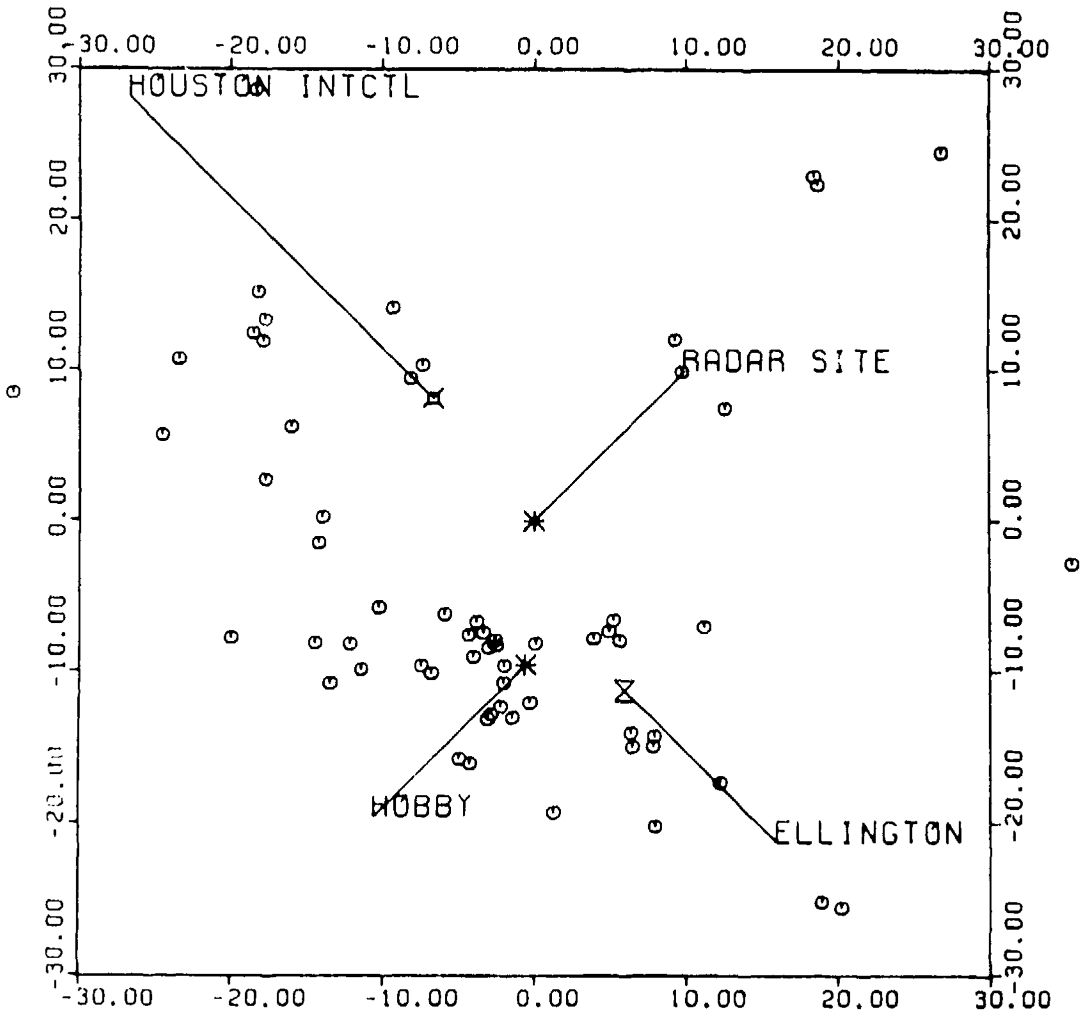


FIGURE 3-11
SELECTED NOMINAL BOUNDARIES AND PARAMETERS BETWEEN PERFORMANCE LEVEL REGIONS



DESENSITIZATION SCHEME OF FIGURE 3-11 IN EFFECT

SCALES IN NAUTICAL MILES

FIGURE 3-12
DISTRIBUTION OF 64 POSITIVE ALERTS USING APPROPRIATE DESENSITIZATION IN EACH REGION

eliminating the range boundaries from the performance level mapping scheme. Instead, a series of altitude transitions in the vicinity of an airport would define the performance level regions. These altitude boundaries would also be airport dependent.

The Houston data shows that maintaining the current joint range/altitude designation for performance level changes has its advantages. Two principle phenomena for which the range/altitude method has an advantage over an altitude-only method are the occurrence of low altitude alerts at some distance from the airports, and the simultaneous use of opposite direction runways. In both instances, the altitude setting selected between performance levels 2 and 3 affects alert generation. In the first situation, setting the altitude boundary too high could cause the inhibiting of a necessary alert. In the latter situation, setting the altitude boundary too low would result in generating an intolerable number of alerts due to the high closing rates of aircraft on final approach to opposite direction runways and to aircraft on the ground. If the RBX is to be placed at airports, the range capability should be utilized in conjunction with altitude. Greater flexibility in shaping performance level regions will result in better control of alert generation.

3.12 Automatic On-Board Performance Level Control

Another alternative for selecting BCAS performance levels is an onboard automatic method of desensitization. Even using the RBX for desensitization, a next-best strategy is needed for those areas where there is no RBX. In place of the RBX, a procedure could be effected whereby altitude would become the sole determinant of performance level. This procedure would utilize radar and barometric altimeter readings to signal the crossing of regions. Another procedure could make use of landing gear and flaps. This method, however, was not analyzed in this study.

Radar and barometric altimeter input to BCAS would be easy to implement. Designating 10,000 feet MSL, as determined from barometric altimeter input, as the boundary between performance levels 5 and 4 would be consistent with the RBX method. Designating the altitude boundary between performance levels 3 and 2 to be between 500 and 700 feet AGL as determined from radar altimeter input, would probably satisfy the requirement for disabling BCAS near the airports. (Without an additional range boundary, a 900 foot altitude cut off would probably be too high.) The difficult boundary is that which lies between performance level 4 and 3; fortunately, the exact location of this boundary is not as critical as that between levels 2 and 3.

Without a performance level 3 region, i.e., if performance level 4 were used everywhere between 10,000 feet and 500 feet, the alert rate would be unacceptably high. Table 3-3 shows a comparison of the number of positive alerts generated in the critical area between 2 and 10 nmi from the airport. For parameter values of 25, 0.3 and 340 (performance level 4), the number of alerts is double that generated by using values of 20, 0.1 and 340 (performance level 3). It is evident that desensitization of BCAS to performance level 3 is necessary near an airport.

In selecting an optimum boundary between performance levels 4 and 3 for altitude only desensitization, emphasis should be placed on how well the recommended 10 nmi boundary can be implemented. It should be noted that radar altimeter data is available only below 2500 feet AGL. A subset of the Houston data was tested to determine the correlation of aircraft above 2500 feet AGL with aircraft beyond 10 nmi from Houston Intercontinental, Hobby, or Ellington Airports. A total of 114 conflicts were considered, all more than 2 nmi from the above airports, with ALIM = 340 feet, TRTHR = 25 seconds, and DMOD = 0.3 nmi (the BCAS logic of Reference 7). They broke down as follows:

	Inside 10 nmi	Outside 10 nmi
Below 2500 feet AGL	83	10
Above 2500 feet AGL	6	15

Ideally, one would desire zeroes in the northeast and southwest quadrants. However, the radar altimeter option in this data base would cause ten conflicts to be desensitized (to level 3) outside 10 nmi, and would cause six conflicts to remain at level 4 although inside 10 nmi. Tables 3-4 and 3-5 show data for these sixteen. Of the ten desensitized conflicts, four were within 5 nmi miles of Hooks Airport, a fifth within 5 nmi of Humphrey Airport, and two more were just outside 10 nmi from Hobby; presumably it would be acceptable to apply level 3 to these seven encounters. Of the six sensitized conflicts, one was 12,000 feet AGL near Houston Intercontinental and one was 6,000 feet AGL near Ellington. The first would occur in level 5, and the second is high enough that it takes on the character of a level 4 rather than a level 3 encounter. Hence the application of level 4 to these encounters would probably be justified. Overall, then, the radar altimeter option causes three undersensitization errors and four oversensitization errors, out of 114 conflicts. All but one (an undersensitization) of these seven involved at least one code 1200 aircraft.

TABLE 3-4

TEN ENCOUNTERS WHICH OCCURRED BEYOND 10 NMI FROM THE THREE HOUSTON AREA AIRPORTS BUT BELOW 2500 FEET AGL

Location of Conflict			Comment	#Code-1200's
X(nmi)	Y(nmi)	Z(ft)		
-18.5	12.4	1400	OK Within 5nmi Hooks Airport	2
-17.6	13.3	1000	OK: Within 5nmi Hooks Airport	1
-18.2	15.2	700	OK: Within 5nmi Hooks Airport	0
-17.9	11.9	800	OK: Within 5nmi Hooks Airport	1
18.1	-2.1	1200	OK: Within 5nmi Humphrey Airport	1
-14.4	-8.1	1400	OK: Within 11nmi Hobby Airport	2
-11.1	-9.7	2300	OK Within 11nmi Hobby Airport	1
The following three cases are judged to be errors of undersensitization				
18.8	-25.1	1900	Both near level	1
21.1	-26.6	1700	Both have diverging vertical rates	1
-18.0	2.7	2100	Both near level	0

Note: x, y, z are midpoints of the aircraft's positions

TABLE 3-5

SIX ENCOUNTERS WHICH OCCURRED WITHIN 10 NMI OF THE THREE HOUSTON AREA AIRPORTS BUT WERE ABOVE 2500 FEET AGL

Location of Conflict					
X(nmi)	Y(nmi)	Z(ft)	Within 10nmi of	Comment	#Code 1200's
-9.4	14.7	12000	Houston Intc Airport	OK-High enough for level 5	0
6.2	-8.1	6100	Ellington Airport	OK-Has character of level 4 conflict	0
The following four cases are judged errors of oversensitization.					
-7.8	3.6	3800	Houston Intc Airport		1
-8.3	-10.2	3400	Hobby Airport		2
-6.9	-10.0	3000	Hobby Airport		2
4.4	-7.5	3400	Ellington Airport		1

Note: x, y, z are midpoints of the aircraft's positions

Altitude-only desensitization is certainly an alternative to the RBX, but the compromise between protection and alert rate would be more difficult to achieve. In addition, less flexibility would be available for airport to airport adaptation.

3.13 Alert Rates Per Performance Level Region

Analysis of individual alert rates per performance level region can provide insight as to whether or not a particular region boundary has been properly placed. A total of 33 positive alerts were generated in the high density performance level 3 region. Individual conflict geometries indicate that many of these alerts are still candidates for elimination. However, rather than further reducing parameter values other steps were taken to reduce the alert number. In Sections 5.1 and 5.2 logic modifications are described which eliminate a number of these unnecessary alerts.

Within performance level 4, 26 positive alerts were generated for the data base. A number of these alerts occurred just beyond the 10 nmi range boundary as shown on the Calcomp distribution plot. Figure 3-13 is one example of an unnecessary performance level 4 alert. The scenario involves two level, 1200-code aircraft beyond 10 nmi from any airport. If at scan 8, the first alert scan, the pilots could acquire each other visually, it would be evident that they were about to cross each other's path with nearly one nmi clearance in range. This alert would be eliminated if it were within the boundaries of performance level 3. While this may be an indication that the boundary between performance levels 3 and 4 may need further adjustment for the Houston environment, the boundary recommendation of this study remains at 10 nmi.

Determining the number of alerts in performance level 5 required two steps. In order to account for any alert candidates above Flight Level 290, the entire potential-conflict data base was initially run using the largest ALIM value of 740 feet. None of the alerts generated included aircraft at altitudes of 18,000 feet or above. Therefore, use of the maximum ALIM value was inappropriate for this data base. Clearly, the recommended value of ALIM for use at altitudes between 18,000 and 29,000 feet of 640 feet would also not produce any alerts between these altitudes. ALIM was consequently reduced to its minimum value of 440 feet and the BCAS logic was rerun. Five positive alerts in performance level 5 resulted from this exercise.

Examination of the aircraft ID's revealed that one of the conflicts was also an alert using performance level 4

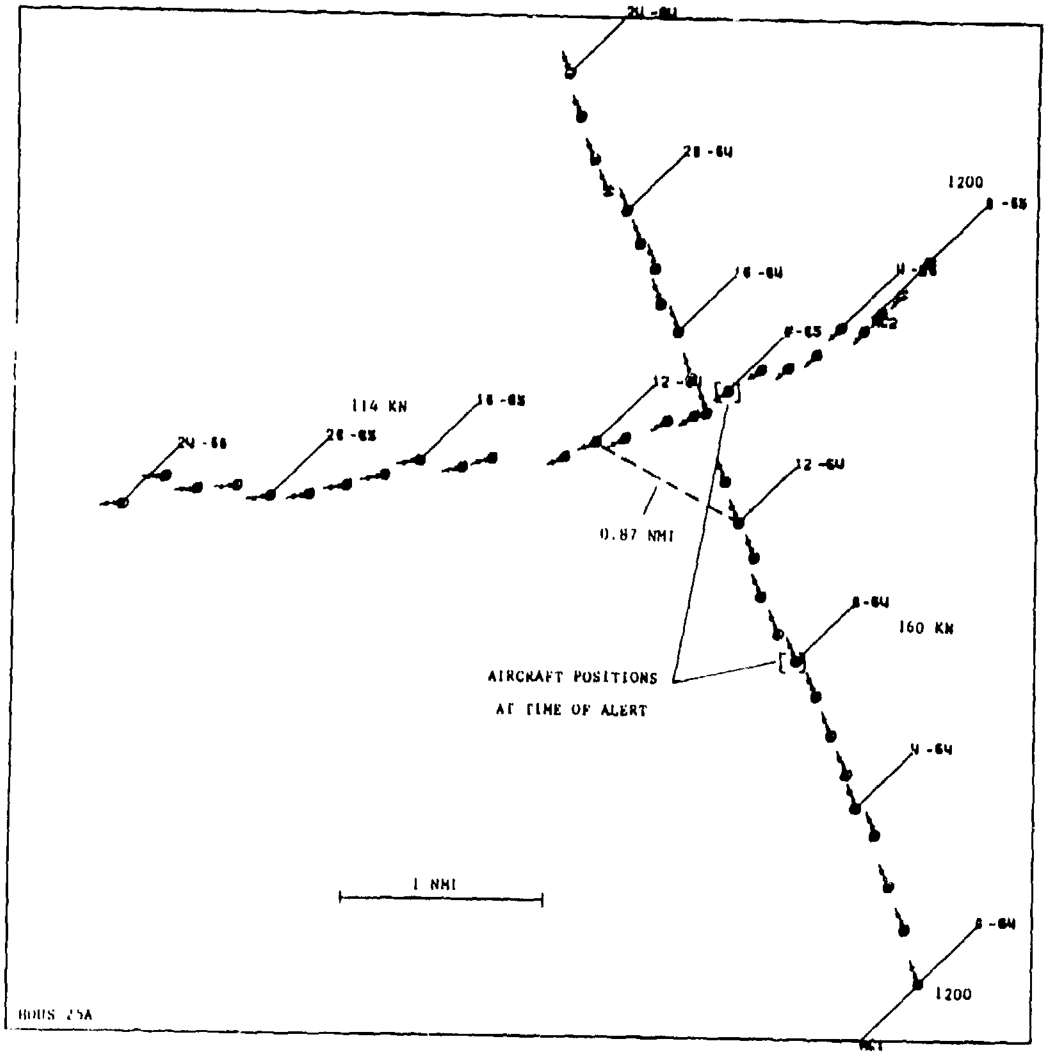


FIGURE 3-13
AN UNNECESSARY POSITIVE ALERT IN PERFORMANCE LEVEL 4 REGION

parameters. The conflict geometry plot of this encounter, Figure 3-14, indicates that the alert was justified. Aircraft 1, a slow speed aircraft, flies level throughout the encounter. Aircraft 2, travelling more than twice the speed of Aircraft 1, climbs through its altitude. The point of closest approach results in only three quarters of a mile separation while the planes are virtually coaltitude. BCAS should not be allowed to give up this type of alert due to desensitization, and in fact, it does not.

Conflict geometry plots of the remaining encounters revealed that the alerts would most likely have been considered unnecessary by the pilots. Separation at closest approach was either 2 nmi horizontally or at least 700 feet vertically. In addition, two of the alerts were found to have been caused by bad data. In both cases, the X, Y position and heading of one aircraft jumped suddenly due to ARTS radar data garble. For an explanation of the cause of such garble, see Appendix B.

Figure 3-15 is a typical performance level 5 unnecessary alert. Aircraft 1 is descending at a rate of almost 800 feet per minute while Aircraft 2 is level. At the point of closest approach, the two aircraft have not come within 2 nmi of one another and are separated vertically by about 400 feet. It is possible that the recommended parameter values of 30 seconds, 1.0 nmi, and 440 feet may be excessive for conflict detection and resolution in the lower region of performance level 5, between 10,000 and 18,000 feet.

3.14 Histograms

Figures 3-16 through 3-22 are graphs showing the distribution of aircraft speeds, altitude, track crossing angle, range, closing speed, and horizontal separation at the time a positive alert was generated. Each of the 64 positive alert encounters is represented in the histograms. Note that the last interval, totaling 100%, includes all counts belonging in that interval plus any higher intervals.

Figure 3-16 depicts the speed distribution. Approximately 50% of all aircraft had speeds of 150 knots or less at the time of the alert. This indicates that there are still many alerts occurring near airports at slower speeds and that the large number of 1200-code aircraft which presumably have lower performance significantly contributed to the Houston alert rate.

Figure 3-17 is a graph showing the frequency of occurrence of various track crossing angles. The track crossing angle is the angle formed by projecting the headings of two aircraft. This

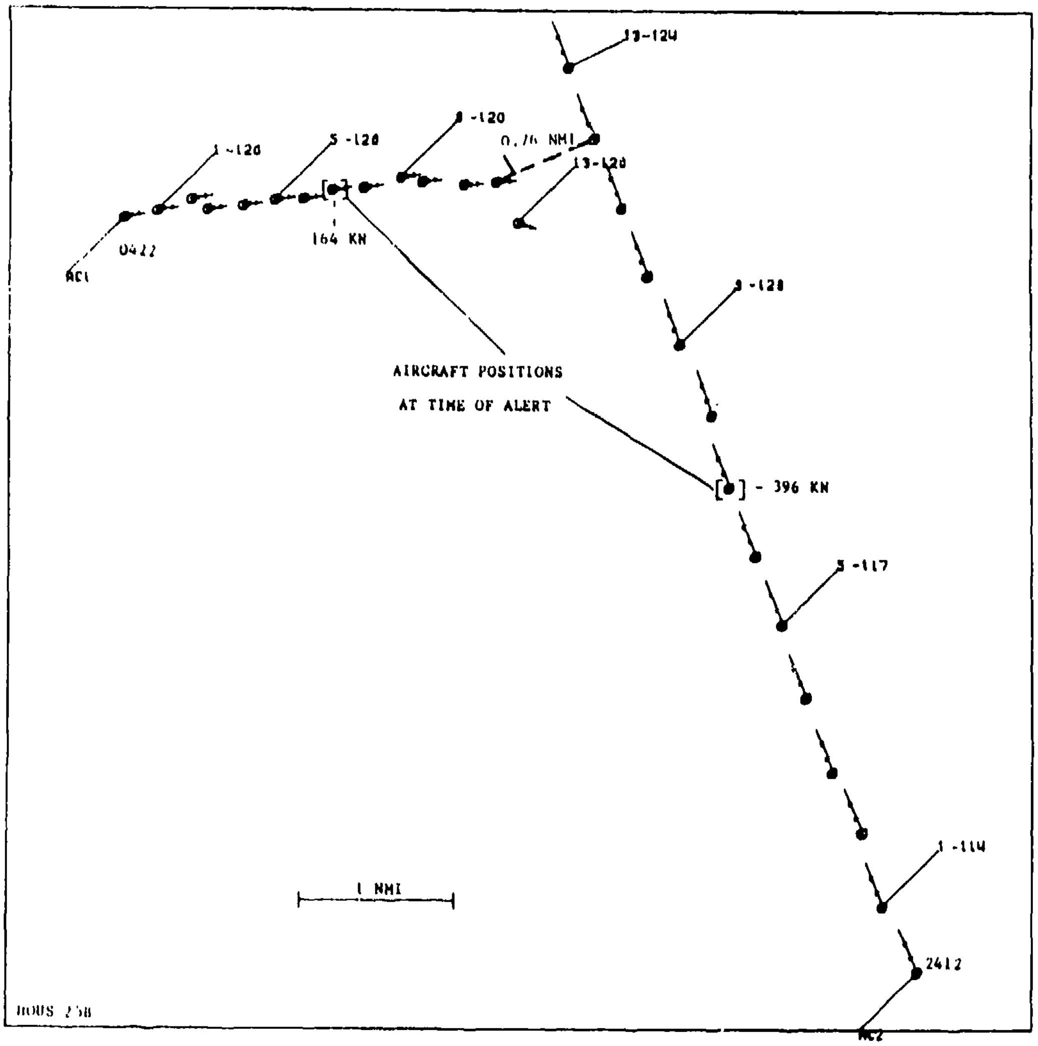


FIGURE 3-14
A JUSTIFIED POSITIVE ALERT IN PERFORMANCE LEVEL 5 REGION

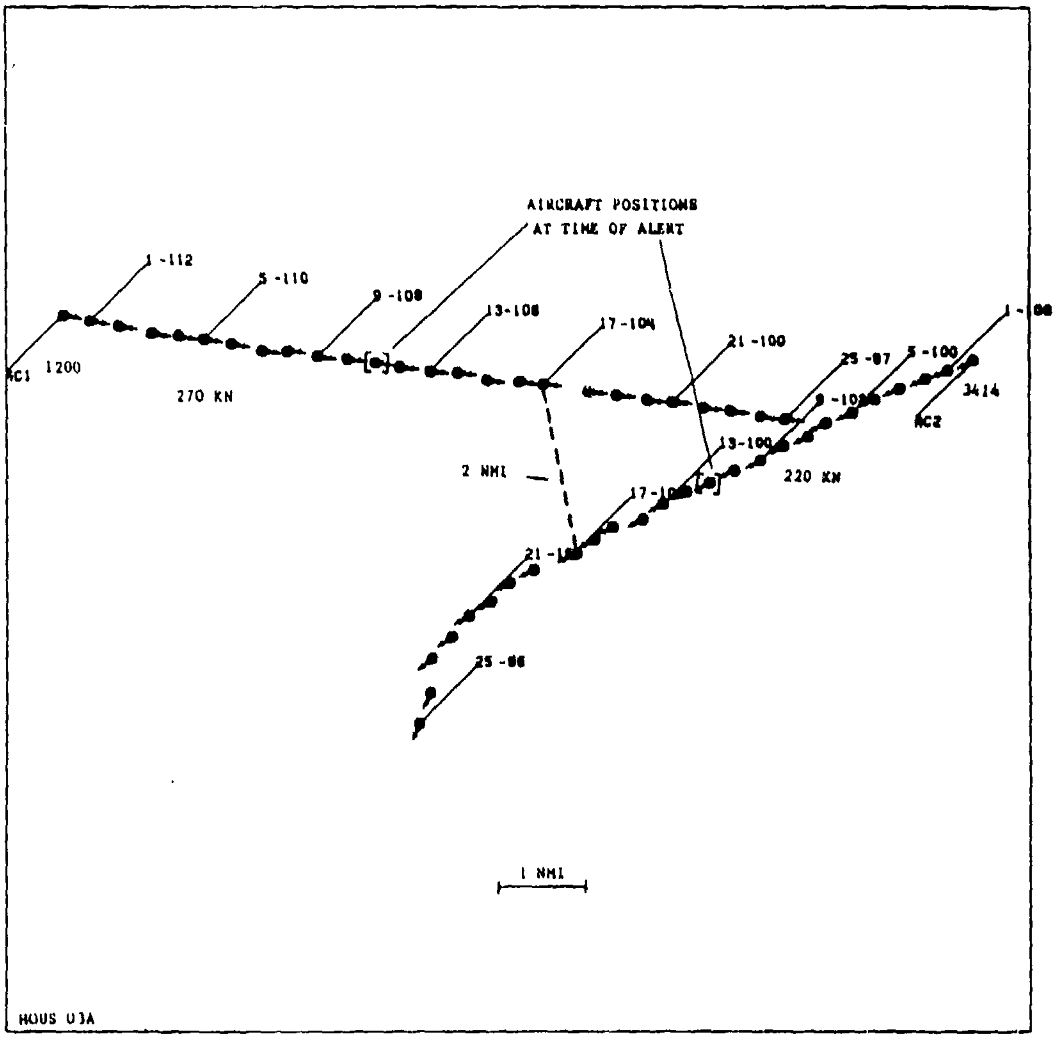


FIGURE 3-15
AN UNNECESSARY POSITIVE ALERT IN PERFORMANCE LEVEL 5 REGION

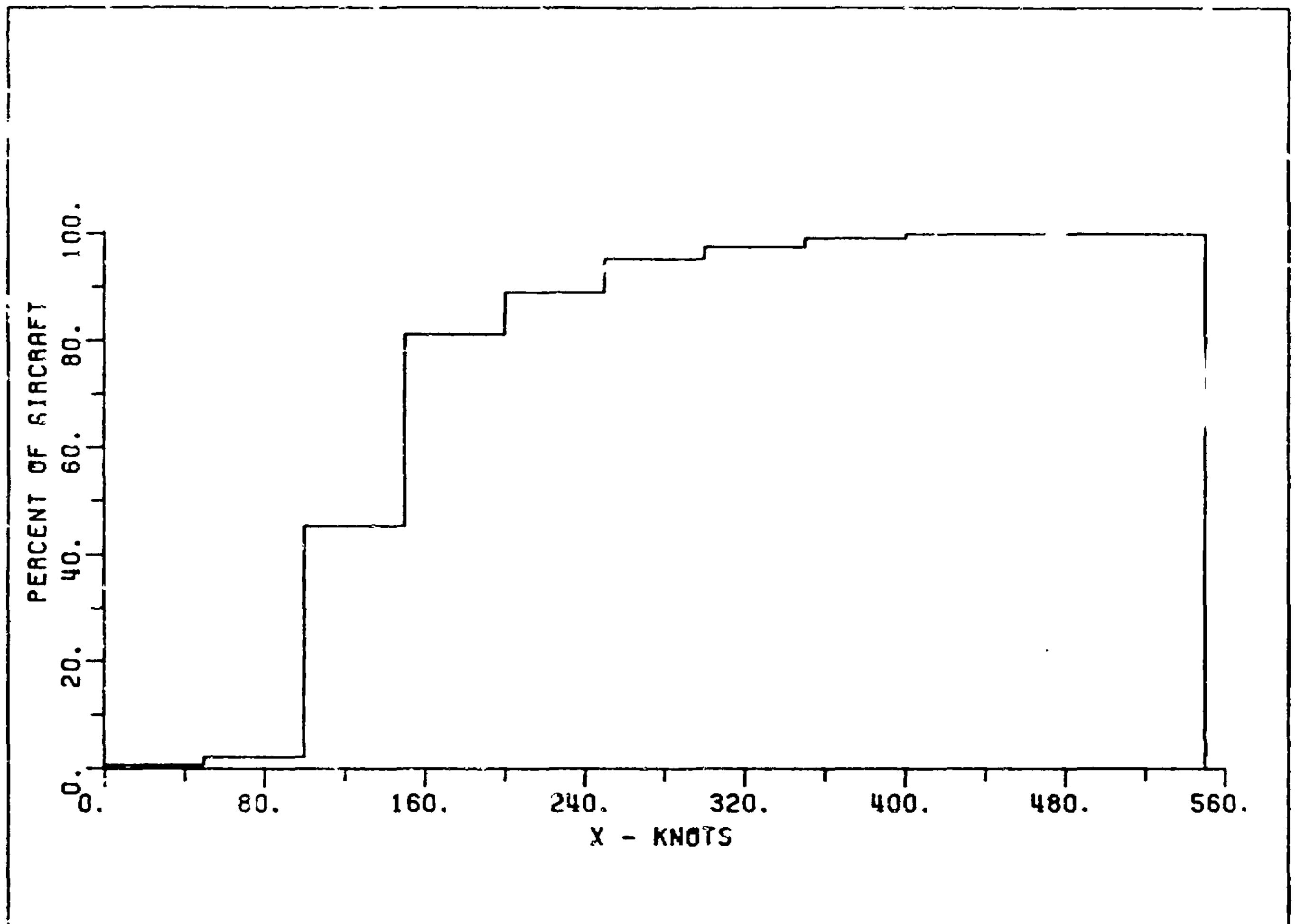


FIGURE 3-16
PERCENT OF AIRCRAFT WITH POSITIVE COMMANDS HAVING SPEEDS LESS THAN X

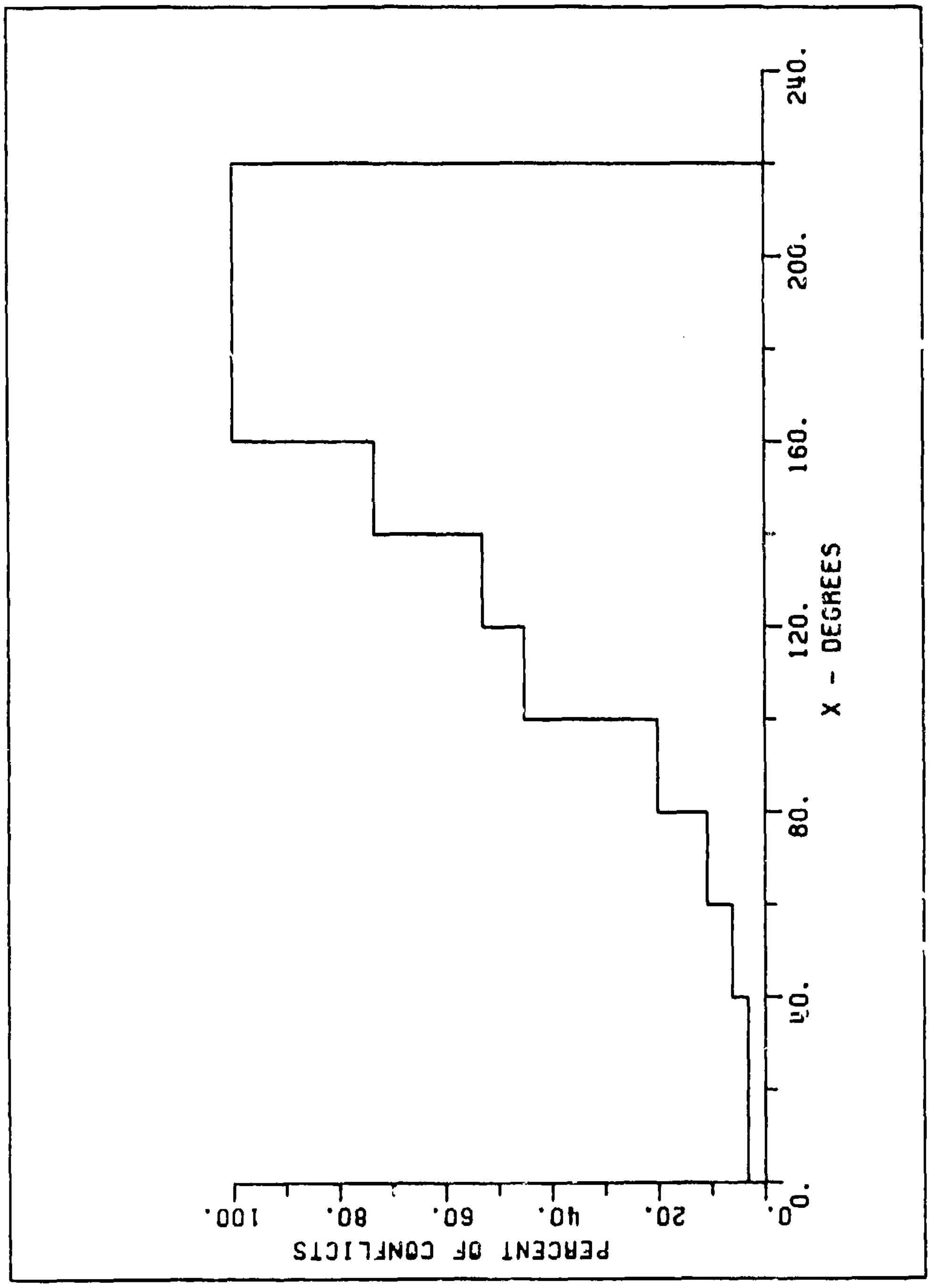


FIGURE 3-17
PERCENT OF CONFLICTS WITH TRACK CROSSING ANGLE LESS THAN X

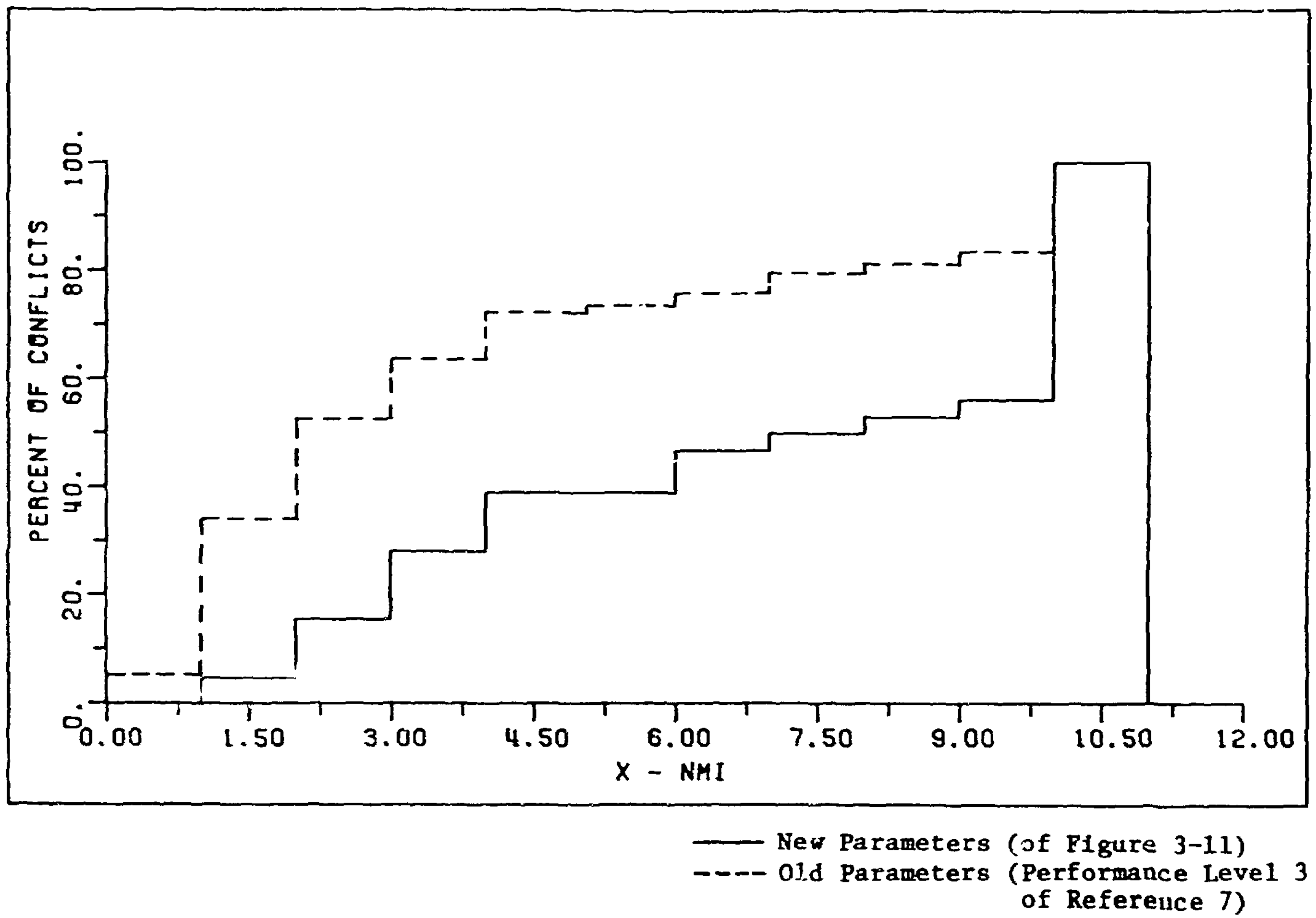


FIGURE 3-18
PERCENT OF CONFLICTS OCCURRING WITHIN X NMI OF CLOSEST AIRPORT

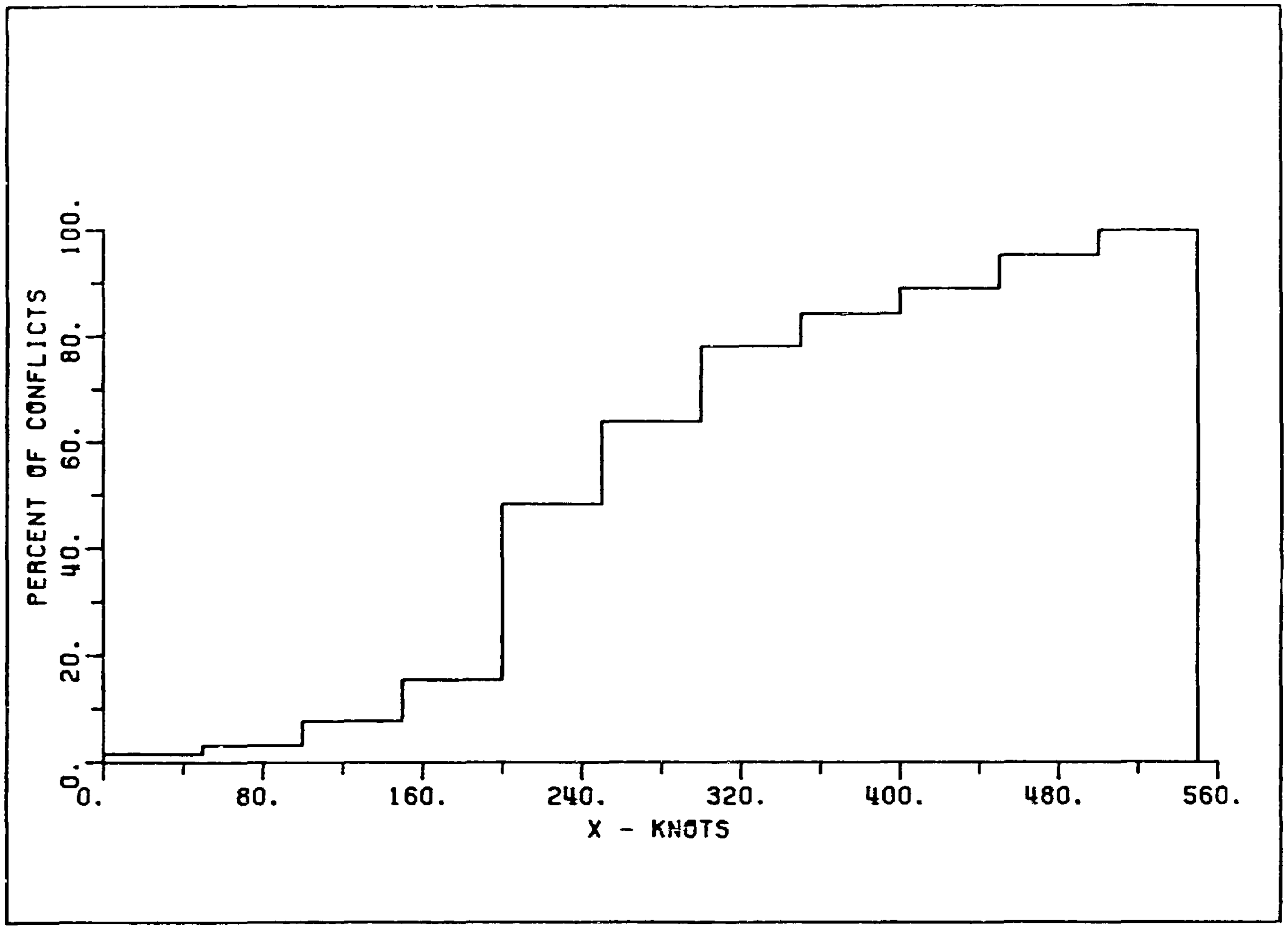


FIGURE 3-19
PERCENT OF CONFLICTS WITH CLOSING SPEED LESS THAN X

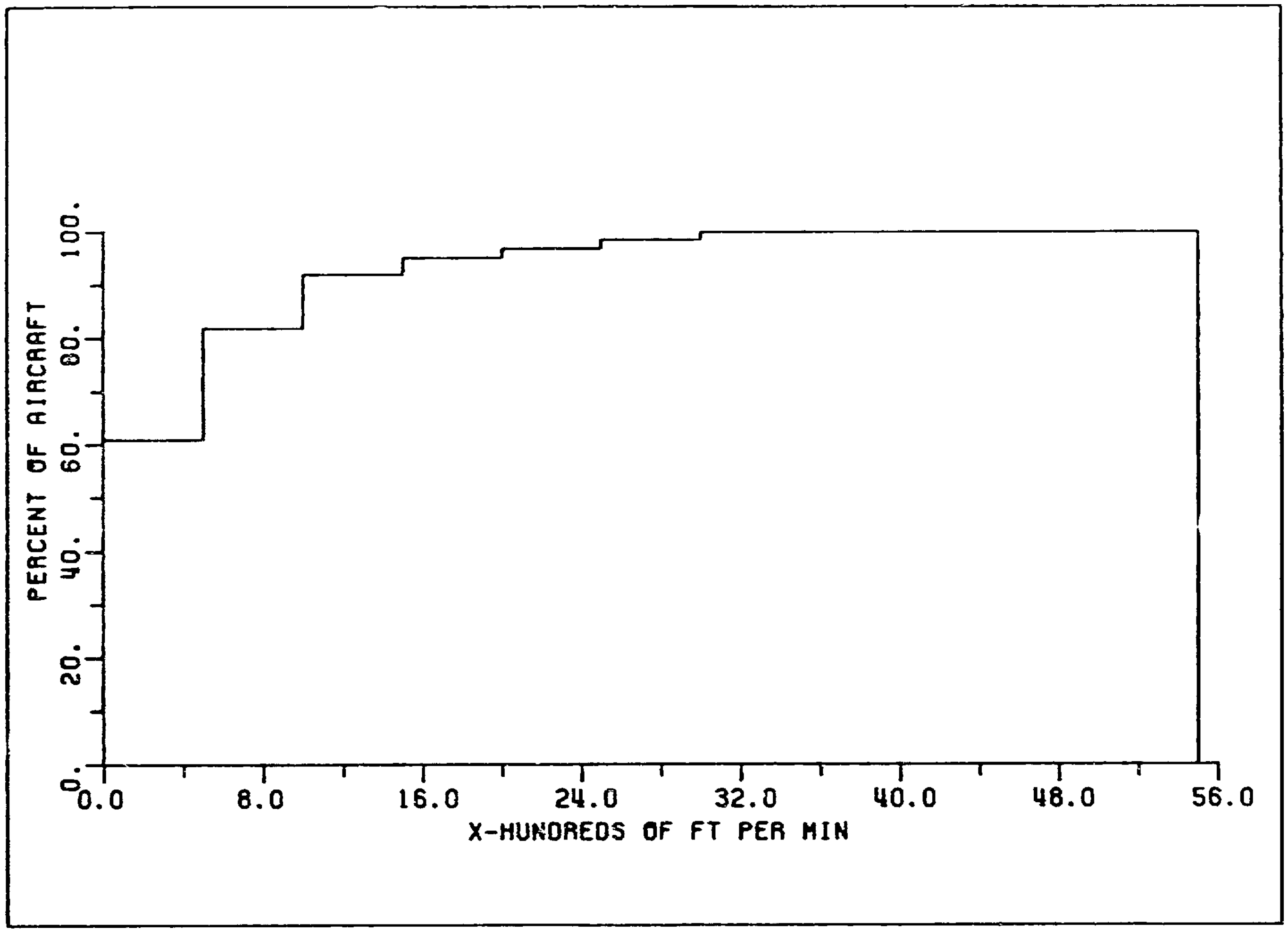


FIGURE 3-20
PERCENT OF AIRCRAFT WITH POSITIVE COMMANDS HAVING VERTICAL SPEEDS LESS THAN X

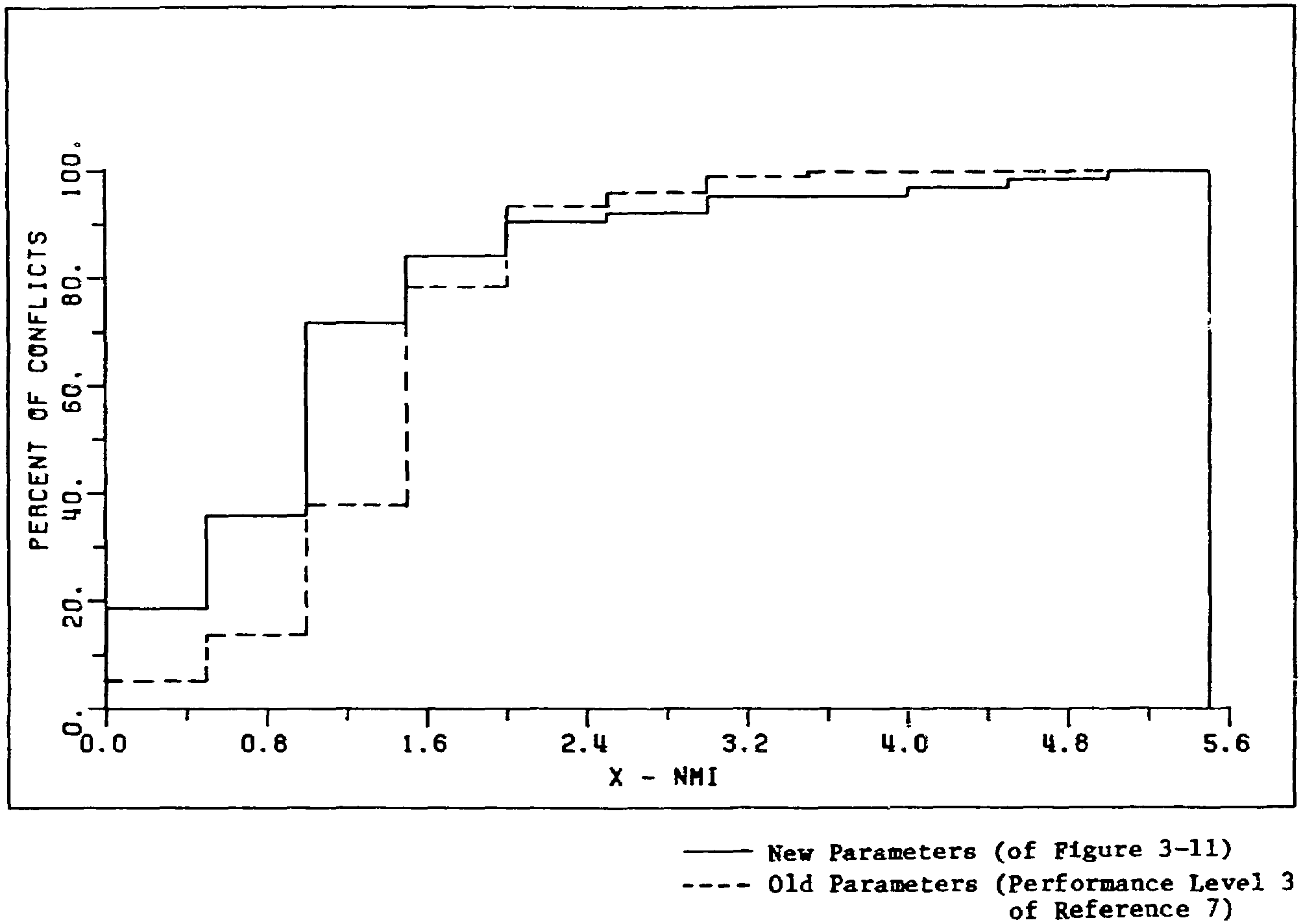
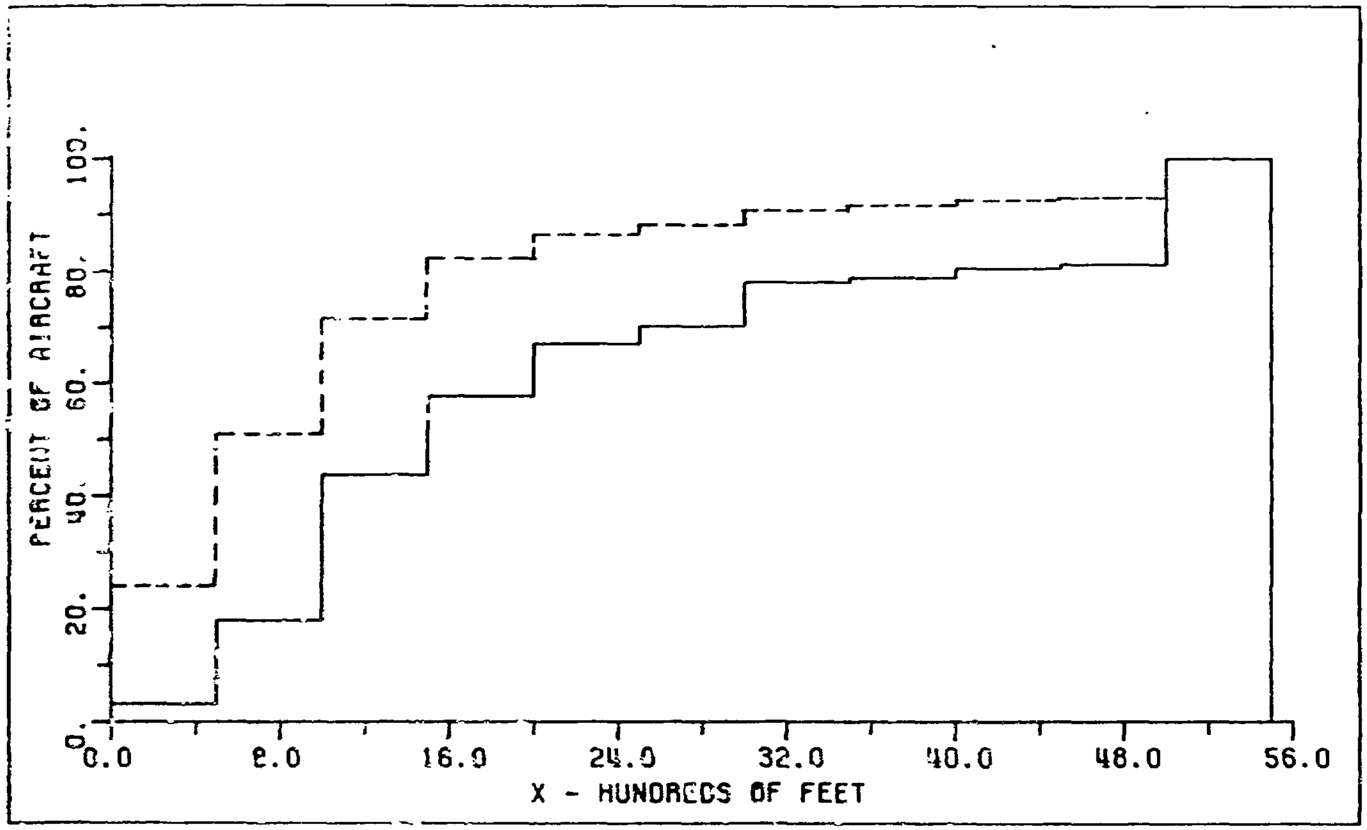


FIGURE 3-21
PERCENT OF CONFLICTS WITH SEPARATION AT BEGINNING OF CONFLICT LESS THAN X



—— New Parameters (of Figure 3-11)
---- Old Parameters (Performance Level 3 of Reference 7)

FIGURE 3-22
PERCENT OF AIRCRAFT WITH POSITIVE COMMANDS HAVING ALTITUDES LESS THAN X

data shows about 50% of the conflicts having track crossing angles of 140 degrees or more. This may be misleading unless the nature of the conflict scenarios is understood. The program which composes the histogram uses only the data received at the first alert scan. The track crossing angle therefore is computed only once, at the time that a positive alert is first given. Although large crossing angle scenarios are present, many encounters in the Houston data base involve turning maneuvers in which two aircraft are in head-on configurations for only a few scans. As the turning maneuver is completed, the conflict changes geometry to a lower track crossing angle and often resolves itself. This situation causes the unusually high number of large track crossing angles to appear in the graph. Of course, BCAS cannot be expected to anticipate these maneuvers. Therefore, turning scenarios will continue to generate some unnecessary alerts.

Figure 3-18 shows the distribution of range from the nearest airport. This histogram also includes data from the 200 alerts generated prior to desensitization. Fewer than 20% of the conflicts using the new parameters occurred within 3 nmi from an airport. This is a large reduction from the 52% shown using the performance level 3 parameters of Table 3-1 for all conflicts and without desensitization of performance level 2. Even with desensitization, alert rates will continue to reflect the higher traffic density close to the airports.

Figure 3-19, the distribution of closing speeds, shows that about half the encounters had closing speeds between 200 and 360 knots. This is a reflection of the low speed, close-in traffic which comprises a large segment of the alert data. In fact, the maximum airspeed permitted by Air Traffic Control for aircraft below 10,000 feet MSL is 250 knots. At the time of the first positive alert, less than 80% of the conflicts were recorded with closing speeds less than 400 knots.

The distribution in Figure 3-20 shows that 60% of the aircraft in conflict had vertical speeds of less than 600 feet per minute at the first positive alert scan. A few aircraft, however, were recorded to have vertical speeds in excess of 2,000 feet per minute. The maximum vertical speed at the time of alert for any aircraft was 3488 fpm.

Figure 3-21 depicts the horizontal separation between two aircraft at the first conflict scan. Using new parameters, more than 70% of the encounters began at ranges of 1.6 nmi or less. Again, this reflects the high number of encounters occurring in the high density areas within the TCA. Aircraft are naturally in tighter configurations near the airports. In addition,

desensitization of parameter values causes the generation of alerts at later scans, therefore initial separation is reduced. The distribution is also shown for the 200 conflicts resulting from the performance level 3 parameter set of Table 3-1. Without desensitization, less than 40% of the conflicts began at less than 1.6 nmi.

Figure 3-22 shows the altitude distribution at the first alert scan. Without desensitization, 50% of the aircraft were below 1,000 feet at the time of the alert. This compares to 20% with desensitization applied. This reduction is due mostly to the inhibition of BCAS close in to the airport at performance level 2.

4. CONFLICT GEOMETRY PLOTS

Conflict geometry plots were used liberally as a means of determining the validity of the alerts for individual encounters. They were also used to measure tradeoffs between lower alert rates and separation protection. Specific conflicts which were eliminated through desensitization of parameters or performance level boundaries were selected for examination. From this data, determinations were made as to whether or not the alerts were justifiably eliminated. The following conflict geometry plots have been selected to illustrate some of the results of desensitization.

4.1 Unnecessary Alerts Eliminated by Desensitization

Figure 4-1 typifies the kind of alert which was generated by conservative parameters and then eliminated through desensitization. In this scenario, which occurs within 10 nmi of Hobby in performance level 3, Aircraft 1 remains level while Aircraft 2 descends. There is about a 50 knot difference in speed and both aircraft are relatively low speed. At the first alert scan, if the pilots were able to make visual contact, the pilot of Aircraft 1 could have seen that Aircraft 2 had already passed the nose of his aircraft. The point of closest approach was in excess of one nmi. Under VMC conditions, this alert would seem to be unnecessary.

4.2 Alerts Which Cannot Be Eliminated Even With Desensitization

Implementation of desensitization techniques alone will not eliminate all unnecessary alerts. In particular, turning maneuvers that cannot be predicted by BCAS can cause a potential conflict geometry to occur for only a few scans.

Figure 4-2 depicts such a turning scenario. The alert occurs outside of Hobby Airport at a low altitude. At the time of the first alert scan, the two aircraft are in a 135 degree angle approach geometry. However, as Aircraft 2 completes its turn at about scan 8, Aircraft 1 has safely crossed its path at a distance of greater than half a mile. In addition, there are indications that the pilot of Aircraft 2, aware of the path of Aircraft 1, deliberately slowed and extended his turn in order to pass safely behind. At closest approach, the aircraft passed within 0.4 nmi with a vertical separation of about 400 feet.

A second example is shown in Figure 4-3. The aircraft are at low altitudes almost 10 nmi from the nearest airport, in this case Ellington AFB. Aircraft 2 is travelling at more than twice

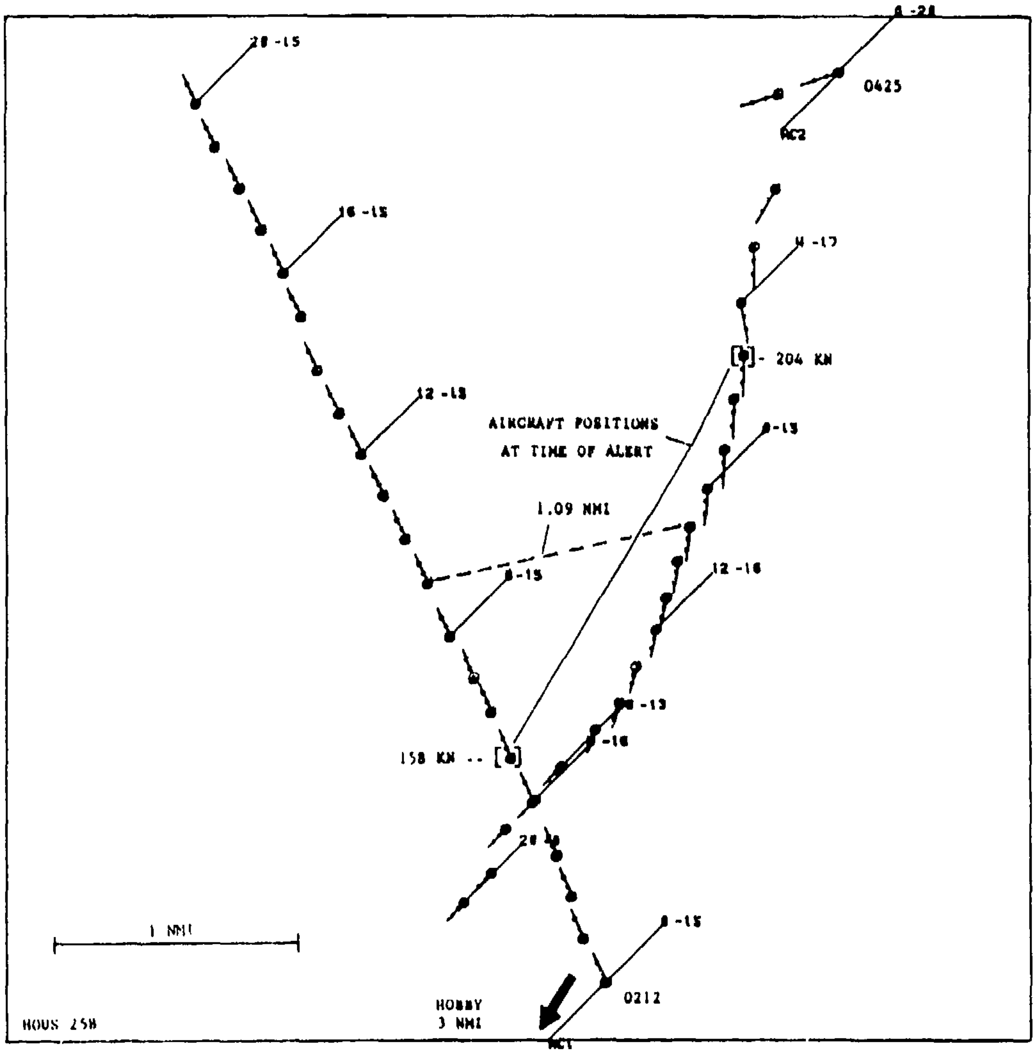


FIGURE 4-1
AN UNNECESSARY POSITIVE ALERT IN PERFORMANCE LEVEL 3
REGION ELIMINATED BY DESENSITIZATION

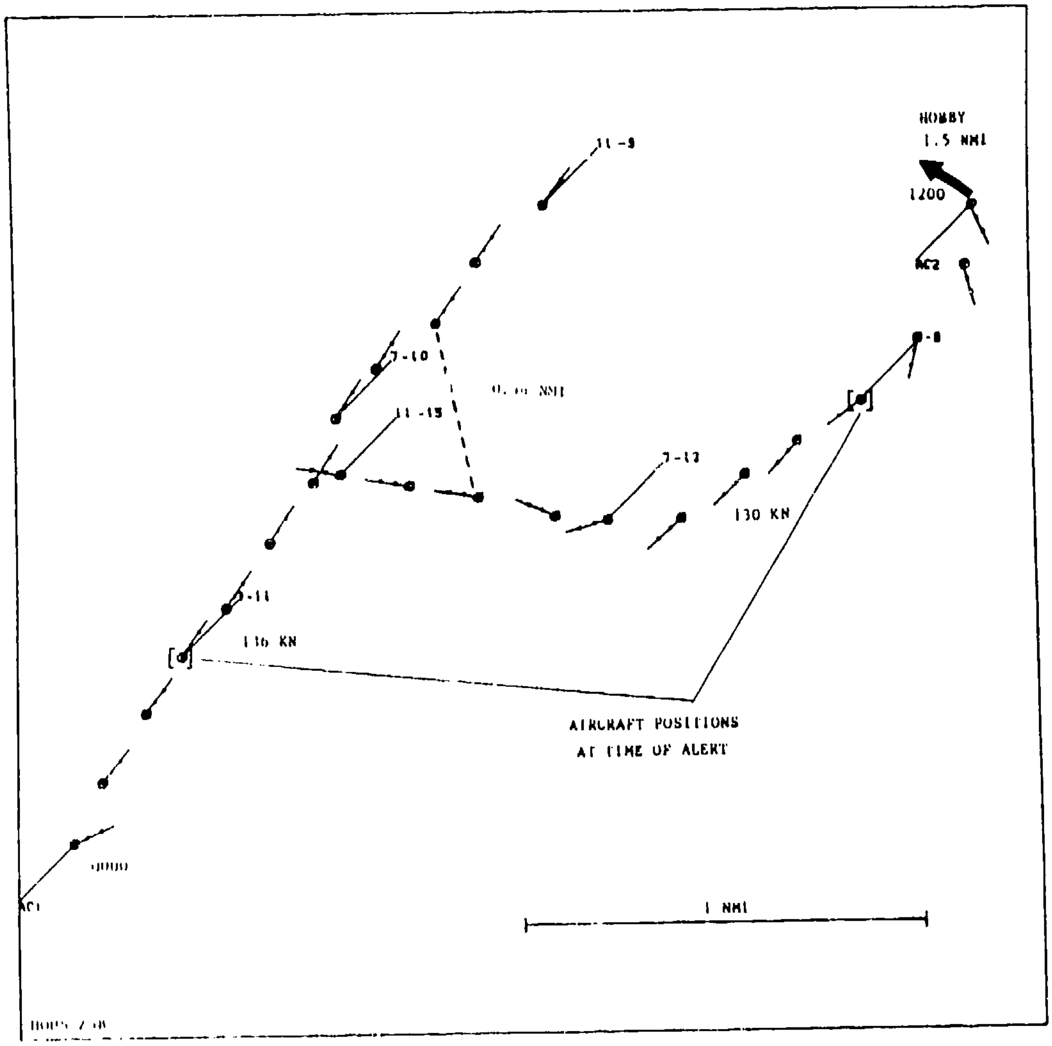


FIGURE 4-2
AN UNNECESSARY POSITIVE ALERT WHICH CANNOT BE ELIMINATED BY DESENSITIZATION

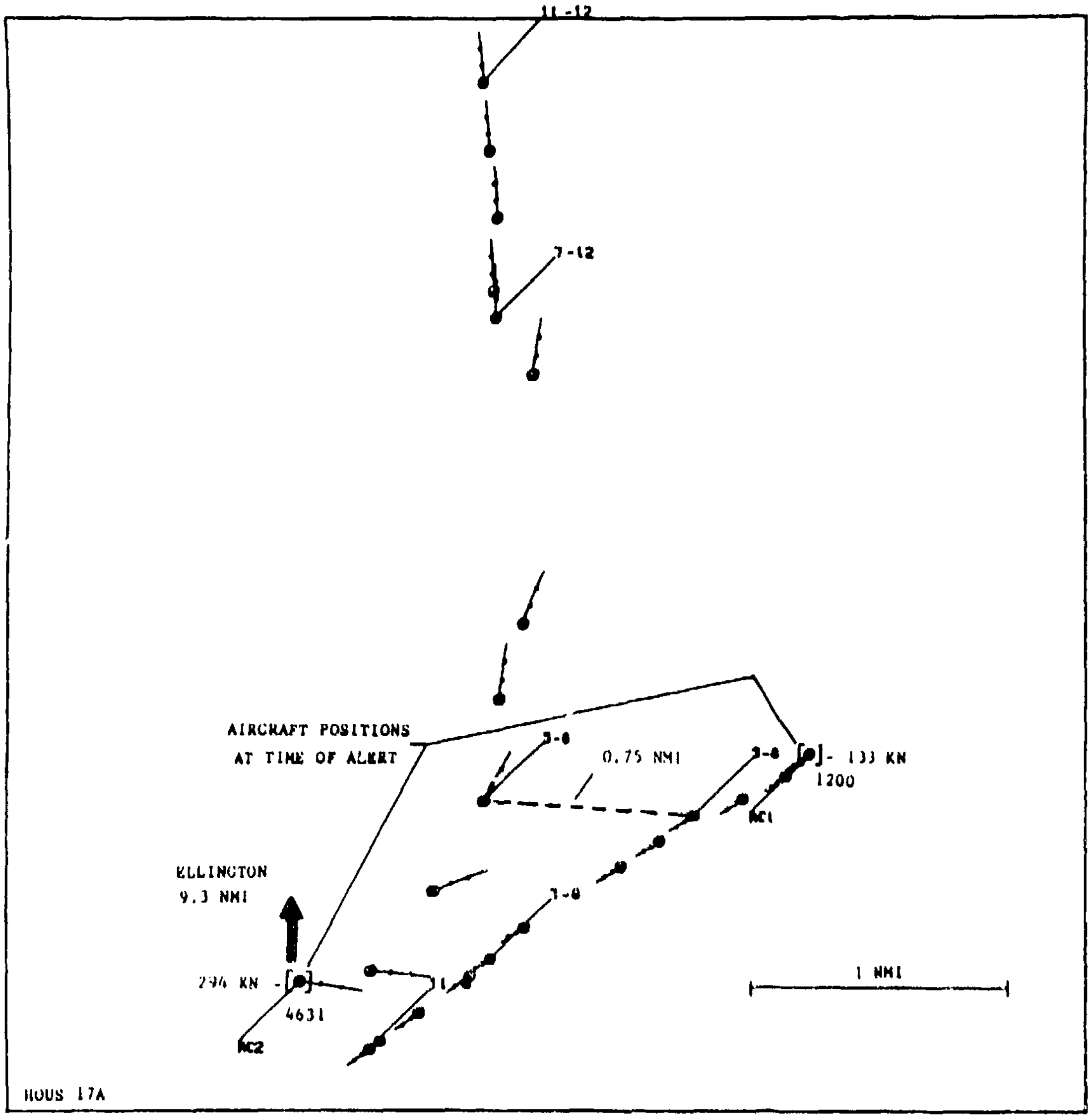


FIGURE 4-3
A LOW ALTITUDE POSITIVE ALERT NOT ELIMINATED BY DESENSITIZATION

the speed of Aircraft 1. The conflict is detected at the first scan, at which time Aircraft 2 is in the process of turning into the path of Aircraft 1. The turning maneuver generates a head-on geometry within 2 more scans before Aircraft 2 finally moves out of the path of the other aircraft. The BCAS tracker cannot predict that the turn initiated by Aircraft 2 will safely clear the path of Aircraft 1. The alert seems justified for at least the first 3 scans.

4.3 Critical Scenarios Resolved by BCAS

Although the Houston data base contains no midair collision data and very few of the aircraft seen by radar ever became 'near miss' encounters, (no Near Midair Incidence Reports for Houston were submitted to the Federal Aviation Administration during this time) a number of scenarios were found which served to test the effectiveness of the BCAS detection logic with and without desensitization.

The first scenario, presented in Figure 4-4, depicts a justified alert within 2 nmi of Hobby. Both the 1200-code and the ATC-code aircraft are climbing and have only a 16 knot difference in speed. Throughout the encounter, the two aircraft maintain a vertical separation of approximately 100 feet. At the first alert scan, Aircraft 1 is in front of Aircraft 2 and is beginning a horizontal maneuver directly into its path. As closest approach nears synchronous garble from the ARTS radar causes tracks to jump. If the bad data point were to be repositioned so as to reasonably be a projection of the previous scan, the effect of this scenario would remain the same. At scans 6 and 7, the horizontal separation is only about 0.2 nmi with a vertical separation of about 100 feet. Even with desensitization in effect this conflict generates a positive alert. This example also gives strong justification for having BCAS operational inside 2 nmi and above an altitude threshold of 900 feet.

The second scenario, Figure 4-5, which occurs beyond 2 nmi of Hobby also suffers from ARTS radar synchronous garble. In addition, missing radar reports and coasting of the data cause obvious problems in generating continuous tracks for the aircraft. However, visual smoothing of the tracks near the area of closest approach conveys that the encounter was in fact a close one. The scenario begins as the two aircraft begin a final approach to Hobby. At the first alert scan, both aircraft are descending through an altitude of about 1300 feet. At scan 20, prior to the garbled reports, the aircraft are separated by

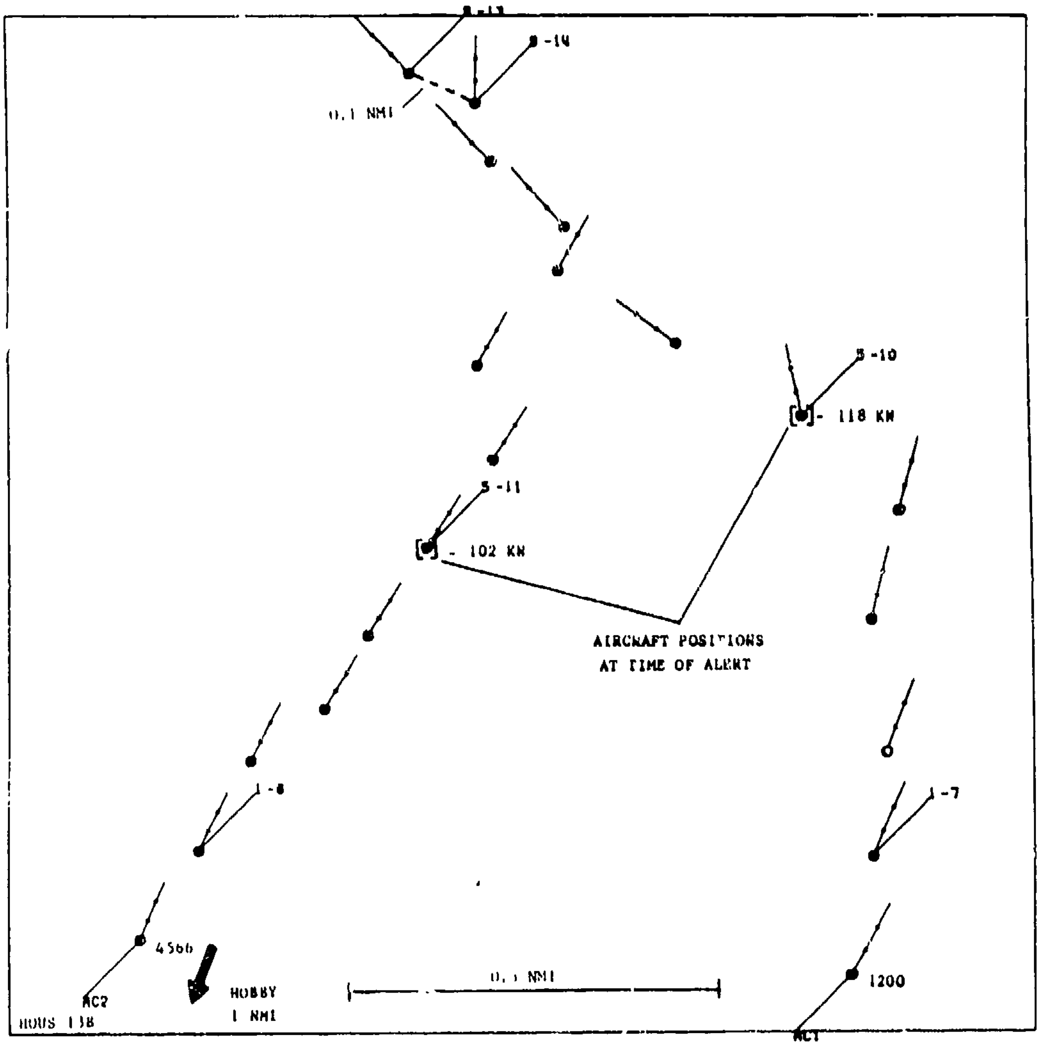


FIGURE 4-4
A JUSTIFIED POSITIVE ALERT INSIDE 2 NMI, ABOVE 900 FEET

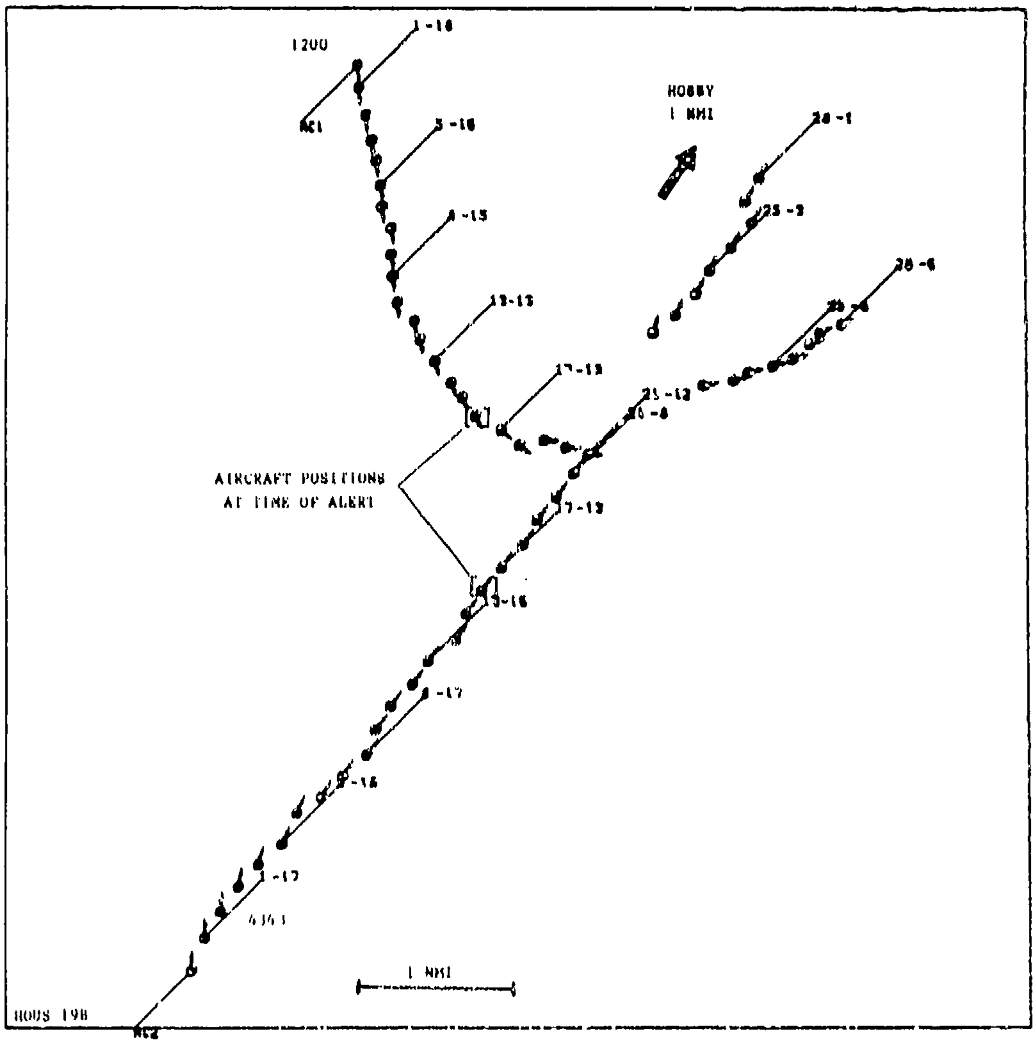


FIGURE 4-5
A JUSTIFIED POSITIVE ALERT IN PERFORMANCE LEVEL 3 REGION

only about 0.3 nmi horizontally an[illegible] 150 feet vertically. In addition as they have not yet [illegible] they are still on a converging course. Desensit[illegible] not cause this alert to be eliminated.

4.4 500 Feet Vertical Separation Res[illegible] IFR and VFR Cruising Altitude Rules

The rules and procedures governing l[illegible] altitude airspace produce 500 foot vertical separations between aircraft as a common occurrence. Per the "Airman's Information Manual Basic Flight Information and ATC Procedures," aircraft cruising in uncontrolled airspace should cruise at altitudes determined by their magnetic course. VFR and IFR aircraft automatically assume even/odd cruising levels staggered by 500 feet vertically. Inside the terminal control area during VMC, a controller can assign altitudes which separate aircraft at 500 foot intervals without adhering to the directional guidelines set forth for uncontrolled airspace. Figure 4-6 shows an example of the 500 foot rule inside the TCA. The two level aircraft, one with an ATC code and one with a 1200 code, are travelling in opposite directions separated by 500 feet. Due to a slight vertical maneuver by one or both of the pilots, vertical separation falls below the ALIM threshold at scan 4 and an alert is generated using the performance level 3 parameters of Table 3-1. It is undesirable however for a positive alert to be generated for such a standard operational geometry. Implementation of desensitized parameters eliminates this positive alert. If either aircraft were equipped with BCAS, it would receive a DON'T CLIMB or DON'T DESCEND alert in this encounter. Reducing the ALIM value from 470 feet to 340 feet provides enough leeway to permit small altitude perturbation without causing positive alerts. (Refer to Section 3.4). At the same time, some protection is afforded in the event that an aircraft legitimately begins a converging vertical maneuver.

4.5 Inhibiting Descend Alerts

The issue of inhibiting BCAS DESCEND alerts when an aircraft drops below a specified altitude above the ground has generated much discussion. In the past, the BCAS logic issued a DON'T CLIMB alert in place of a DESCEND alert when an aircraft was below 1000 feet Above Ground Level (AGL). The objection to not directly displaying a DESCEND alert for situations in which BCAS has tracked an intruder descending upon its own aircraft is that this would, in essence, be deceiving the BCAS pilot. The pilot should have the right to know when BCAS detects danger. With only a DON'T CLIMB displayed, the pilot has no way to

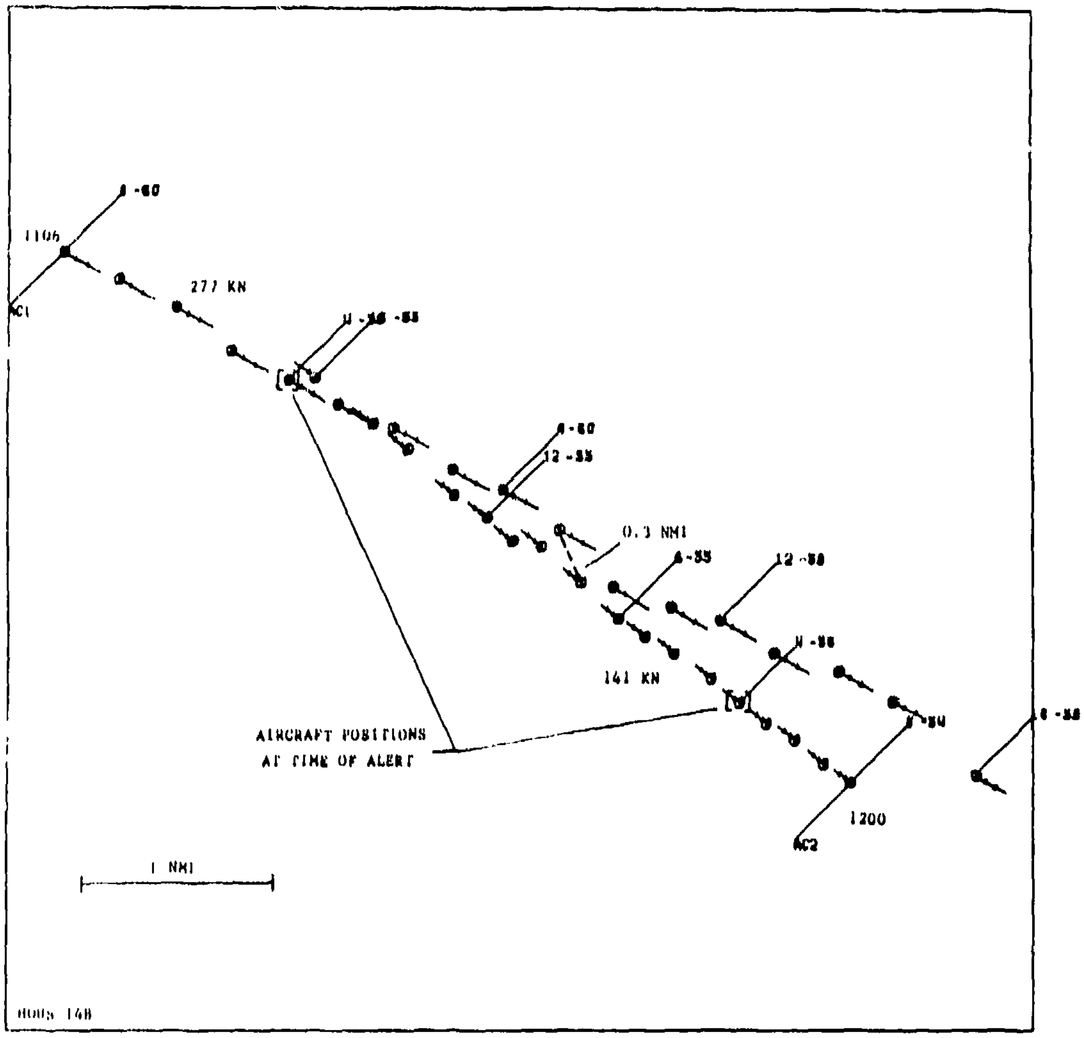


FIGURE 4-6
AN EXAMPLE OF HOW DESENSITIZED ALIM ALLOWS THE 500 FOOT RULE TO WORK INSIDE THE TCA

differentiate between this threatening situation and another less serious situation which only warrants a DON'T CLIMB alert. On the other hand, commanding a pilot to descend when he is already at a low altitude does not appear to be advisable either.

As a result of much analysis, a compromise was made, reducing the 1000 foot boundary for inhibiting a DESCEND alert to 500 feet AGL. This allows a DESCEND alert to be displayed down to an altitude of 500 feet above the ground. Below this altitude, any DESCEND alert generated by the BCAS logic will be displayed as a DON'T CLIMB alert to the pilot.

Figure 4-7 shows one situation in which BCAS resolutions should not be constrained below 1000 feet. This example was also used in Section 4.2 as an alert which cannot be eliminated even with desensitization. The aircraft are at low altitudes almost 10 nmi from the nearest airport, in this case Ellington AFB. Aircraft 2 is travelling at more than twice the speed of Aircraft 1. The conflict is detected at the first scan, at which time Aircraft 2 is in the process of turning into the path of Aircraft 1. The turning maneuver generates a head-on geometry within 2 more scans before Aircraft 2 finally moves out of the path of the other aircraft. The BCAS tracker cannot predict that the turn initiated by Aircraft 2 will safely clear the path of Aircraft 1. The alert seems justified for at least the first 3 scans. This type of low altitude maneuvering was not uncommon in the Houston data base. It therefore appears desirable to allow descend alerts to be displayed to a pilot below 1000 feet. Lowering the threshold to 500 feet seems appropriate for the Houston area.

4.6 Multiple Runway Use

As was indicated in Section 3.2, runway use has a significant effect on the BCAS desensitization effort. In addition to individual aircraft plots of tracked encounters, another plotting technique was implemented which revealed use of several runway patterns with implications for the BCAS logic.

Figures 4-8 through 4-10 are plots of actual ARTS radar target reports at Houston and Hobby Airports. No smoothing or filtering has been performed on these reports. Each plot represents approximately 10 minutes of traffic operations. The large type alphabetic characters denote time. The beginning scan of the plot is represented by the letter 'A' (0 seconds). Each successive letter of the alphabet is used at 30 second intervals, so that 'B' indicates that 30 seconds have passed, etc. The time intervals are followed by smaller alphanumeric characters (1-9, A-Z) representing the altitude of the aircraft in increments of 500 feet. Table 4-1 is a key to each symbol on the plots.

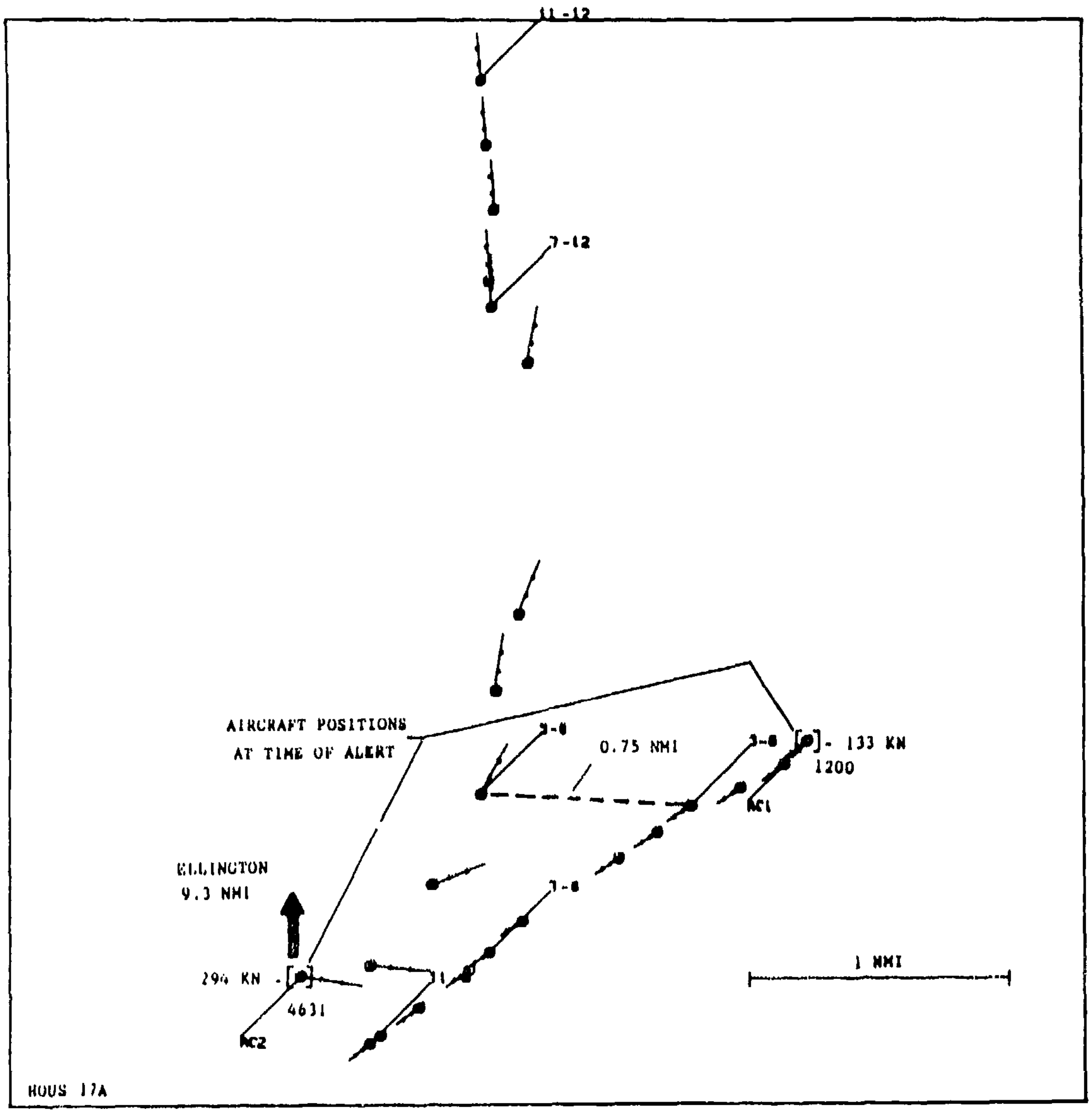


FIGURE 4-7
AN EXAMPLE SHOWING WHY BCAS SHOULD NOT BE INHIBITED BELOW 1000 FEET

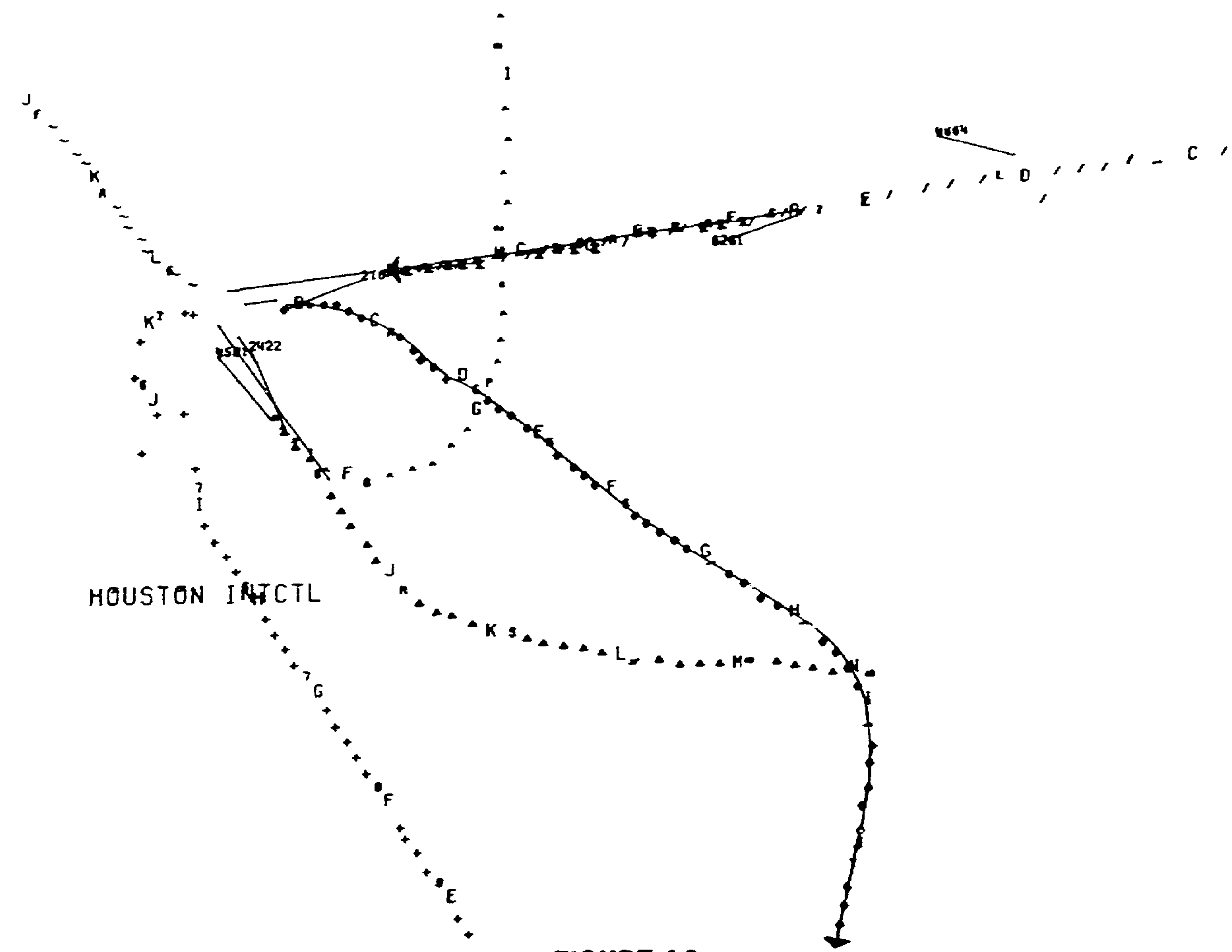


FIGURE 4-8
SIMULTANEOUS USE OF PARALLEL RUNWAYS FOR OPPOSITE DIRECTION TAKE-OFF AND LANDING AT HOUSTON AIRPORT

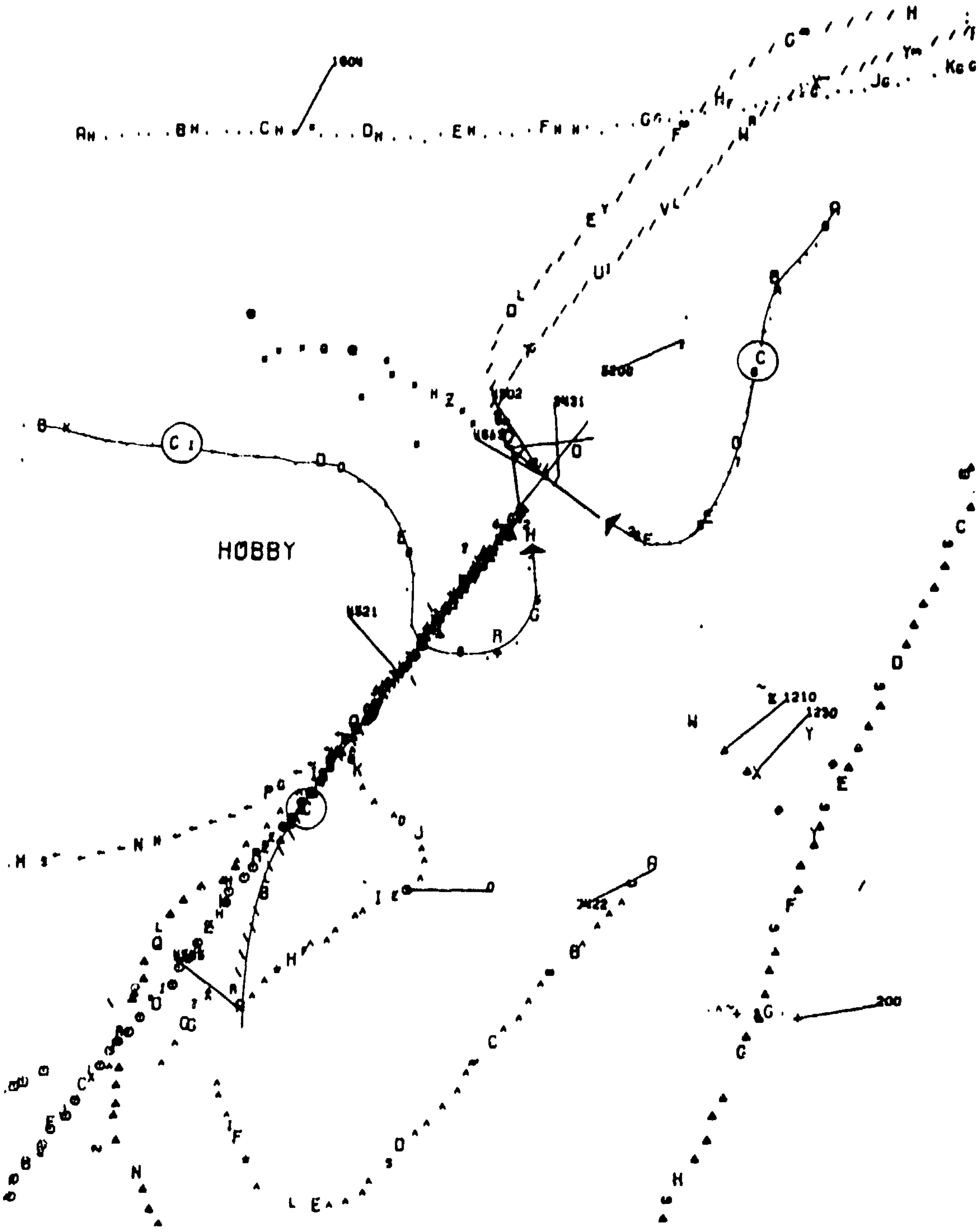


FIGURE 4-9
SIMULTANEOUS USE OF THREE INTERSECTING RUNWAYS AT HOBBY AIRPORT

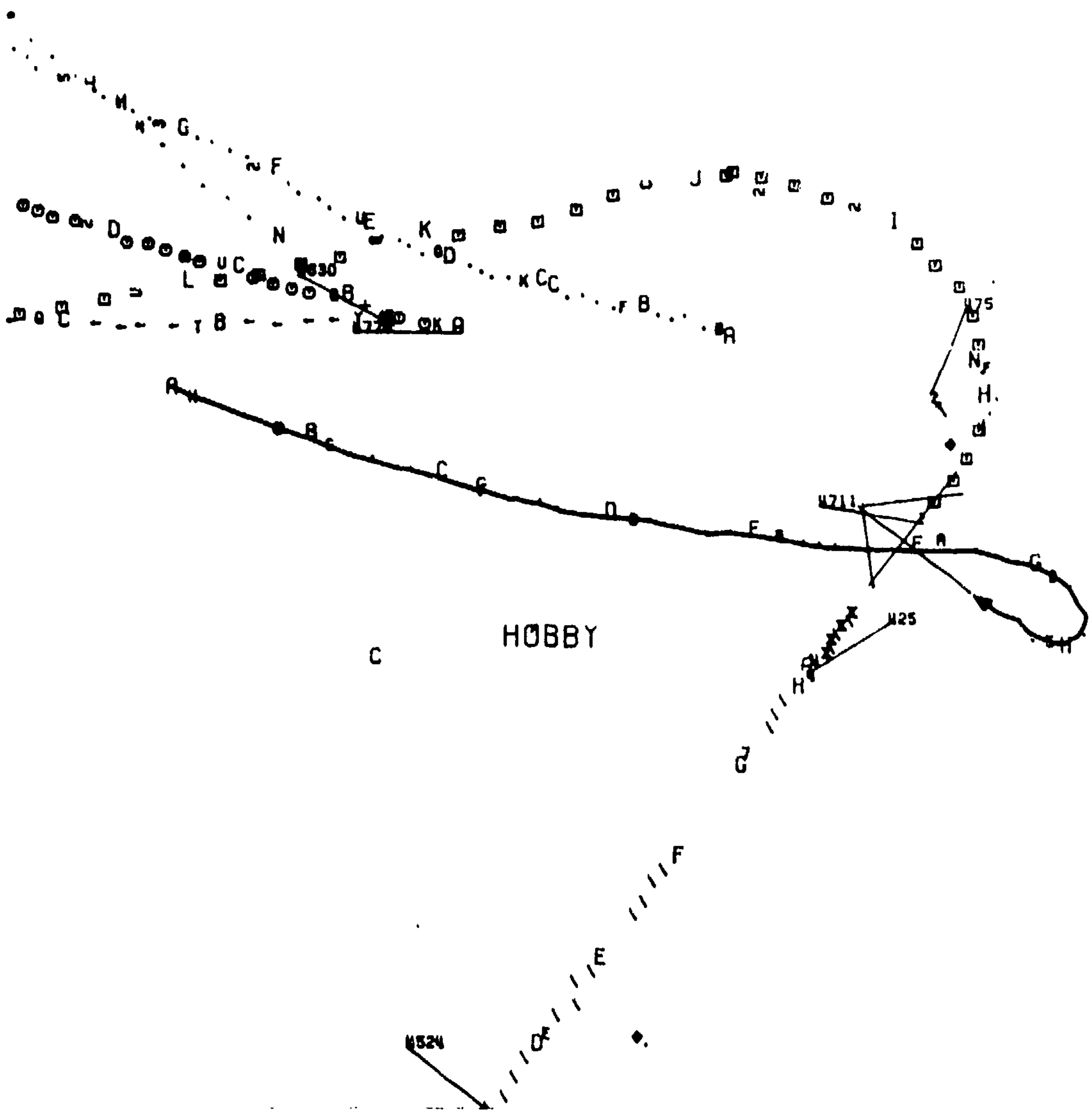


FIGURE 4-10
AIRCRAFT FLIES OVER HOBBY AIRFIELD BEFORE LANDING

TABLE 4-1

LIST OF SYMBOLS FOR ARTS RADAR PLOTS

Time in Seconds		Altitude in Hundreds of Feet	
Symbol	Meaning	Symbol	Meaning
A	0	?	0
B	30	1	1
C	60	2	2
D	90	3	3
E	120	4	4
F	150	5	5
G	180	6	6
H	210	7	7
I	240	8	8
J	270	9	9
K	300	A	10
L	330	B	11
M	360	C	12
N	390	D	13
P	420	E	14
Q	450	F	15
R	480	G	16
S	510	H	17
T	540	I	18
U	570	J	19
V	600	K	20
W	630	L	21
X	660	M	22
Y	690	N	23
Z	720	P	24

The next symbol on the plot is used to distinguish individual aircraft with a unique character. The characters are separated by 4.7 seconds, the length of an ARTS radar scan. It was necessary due to symbol shortages to sometimes use the same symbol for more than one aircraft on a plot. The beacon code of each aircraft is attached to the first scan of the track. Individual aircraft tracks are clearly discernible. An arrow has been placed along each track to indicate at a glance the direction of travel. Due to the duration of the data samples, tracks sometimes overlap. Runways have been labelled as they appear at Houston and Hobby Airports.

Figure 4-8 depicts the simultaneous use of parallel runways for opposite direction take-off and landing at Houston Intercontinental. In this particular scenario, runway 26 is being used for a landing while runway 9S, separated by only 1,000 feet, is being used for a departure. The two aircraft are in a head-on configuration for at least 5 scans, or 25 seconds before the departing aircraft begins its right turn. At time 'D' the two aircraft are separated by 1.5 nmi. BCAS could not tolerate such closing geometries and must therefore be disabled.

Figure 4-9 illustrates the use of 3 intersecting runways for nearly simultaneous landings at Hobby Airport. Note the positions of the 3 aircraft at time 'C'. In this particular scenario, one pair of aircraft land within 30 seconds of each other, followed by the third aircraft landing 30 seconds later. These high closing rate encounters are normal operations at airports such as Hobby.

In addition, at Hobby, aircraft have been observed flying over the airfield in order to position themselves for potential landing on a runway. In Figure 4-10 Aircraft 1 flies over the field at 1,100 feet before landing on runway 31. This example gives strong justification for preserving BCAS operation above an altitude boundary at the airports. If aircraft were to come into conflict with one another during such an approach, BCAS should be operational because these operations are essentially random and do not conform to a routine pattern. One pilot cannot infer the intentions of another as readily as when they are both following a normal approach.

Occurrences such as those described above strengthen the need for discriminatory close-in desensitization of BCAS.

4.7 Multiple Encounters

Incorporated into the Active BCAS logic is the capability to detect and resolve multiple aircraft conflicts. The performance of BCAS in these scenarios is a significant aspect worth studying. In order to do so, all encounters in the Houston data base occurring within 600 seconds of each other and involving the same aircraft were extracted. This data was manually reviewed for encounters in which one aircraft was simultaneously in conflict with at least two other aircraft. Two such situations were found. One of the scenarios occurred on short final approach due to normal patterns at Houston Intercontinental. Because BCAS would surely be disabled due to the desensitization scheme, this encounter was not regarded as a true multiple conflict.

The second scenario, however, was found to be a legitimate multiple encounter. Figure 4-11 shows that the aircraft with beacon code 0233 comes into conflict with beacon code 0761 initially, and then with 0205 on the subsequent scan. All aircraft are beyond 2 nmi of Ellington AFB. Therefore, BCAS would not have been disabled in this region.

Desensitizing BCAS parameters in performance level 3, however, does affect this particular multiple encounter. The aircraft with beacon code 0761 is a threat to aircraft 0233 using the performance level 4 parameters of 25 second TRTHR, 0.3 nmi DMOD, and 340 feet ALIM. However, the aircraft are no longer in conflict using 20 seconds, 0.1 nmi, 340 feet for TRTHR, DMOD and ALIM (performance level 3). The encounter returns to a single aircraft pair alert. This effect does not by any means preclude the need for multiple encounter logic.

In addition, this encounter gives further credence to lowering the threshold for inhibiting DESCEND alerts from 1000 feet to 500 feet. See Section 4.5. Reducing the frequency of occurrence of multiple encounters through desensitization is desirable. Because the BCAS logic has no bearing information, it can provide limited resolution options, CLIMB or DESCEND only. As such, multiple encounters, particularly involving two unequipped intruders, in effect reduce the ability of BCAS to resolve conflicts and should not be incurred except where truly close separations are involved.

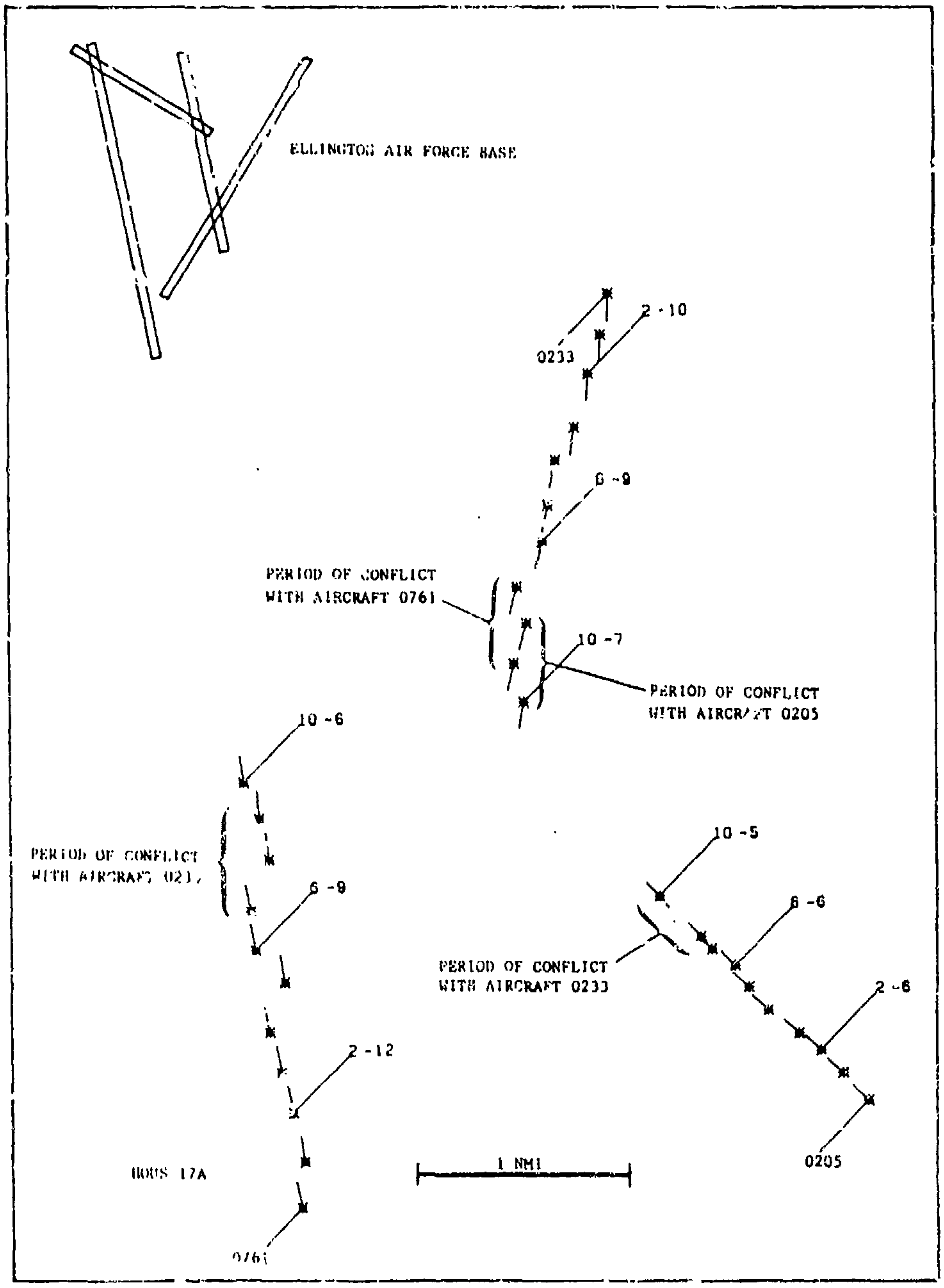


FIGURE 4-11
MULTIPLE AIRCRAFT ENCOUNTER OCCURRING AT MORE THAN 5 NMI FROM CLOSEST AIRPORT

5. LOGIC UPDATES

Earlier in this study references were made to internal modifications which are being incorporated into the BCAS logic. The following sections describe two such updates and their effect on the Houston data base alert rate.

5.1 Vertical Divergence Logic

The vertical divergence logic instituted in the current version of the BCAS logic eliminates unnecessary positive alerts for specific scenarios involving non-simultaneous horizontal and vertical closest approaches. In these scenarios, the vertical divergence logic inhibits positive alerts if the aircraft pair is projected to have at least a specified vertical separation and to be diverging vertically at the time of closest slant range. The logic allows each aircraft, if it has a vertical rate, to continue its vertical motion without disruption. The logic may issue a negative alert which will not require a change in the established vertical rates.

Figure 5-1 shows the modification made to the flowchart appearing in Figure 2-3(b). The modification is indicated by the dotted area of the flowchart.

Figure 5-2 is a typical example of a positive alert which was eliminated by the divergence logic. Aircraft 2 is descending through the altitude of Aircraft 1, which is level. At the time the positive alert would have been generated, at Scan 7, the two aircraft have already crossed in altitude and are separated by 100 feet vertically. By the time horizontal closest approach is reached, the aircraft have achieved 800 feet vertical separation and 0.7 nmi horizontal separation. A positive alert in this scenario is unnecessary.

In the second example, Figure 5-3 shows Aircraft 1 flying level while Aircraft 2 is climbing from an altitude of about 7,500 feet. The speed of Aircraft 2 is approximately 470 knots at scan 10. Without vertical divergence logic, an alert would have been generated at this time. However, Aircraft 2 is already about 100 feet above the other aircraft and climbing at a rate of 3078 fpm. At closest approach, scan 13, vertical separation has increased to almost 700 feet and horizontal separation to 5,900 feet.

All results presented thus far in this report were obtained from the BCAS logic without the vertical divergence logic for eliminating positive alerts. When the Houston data base was run

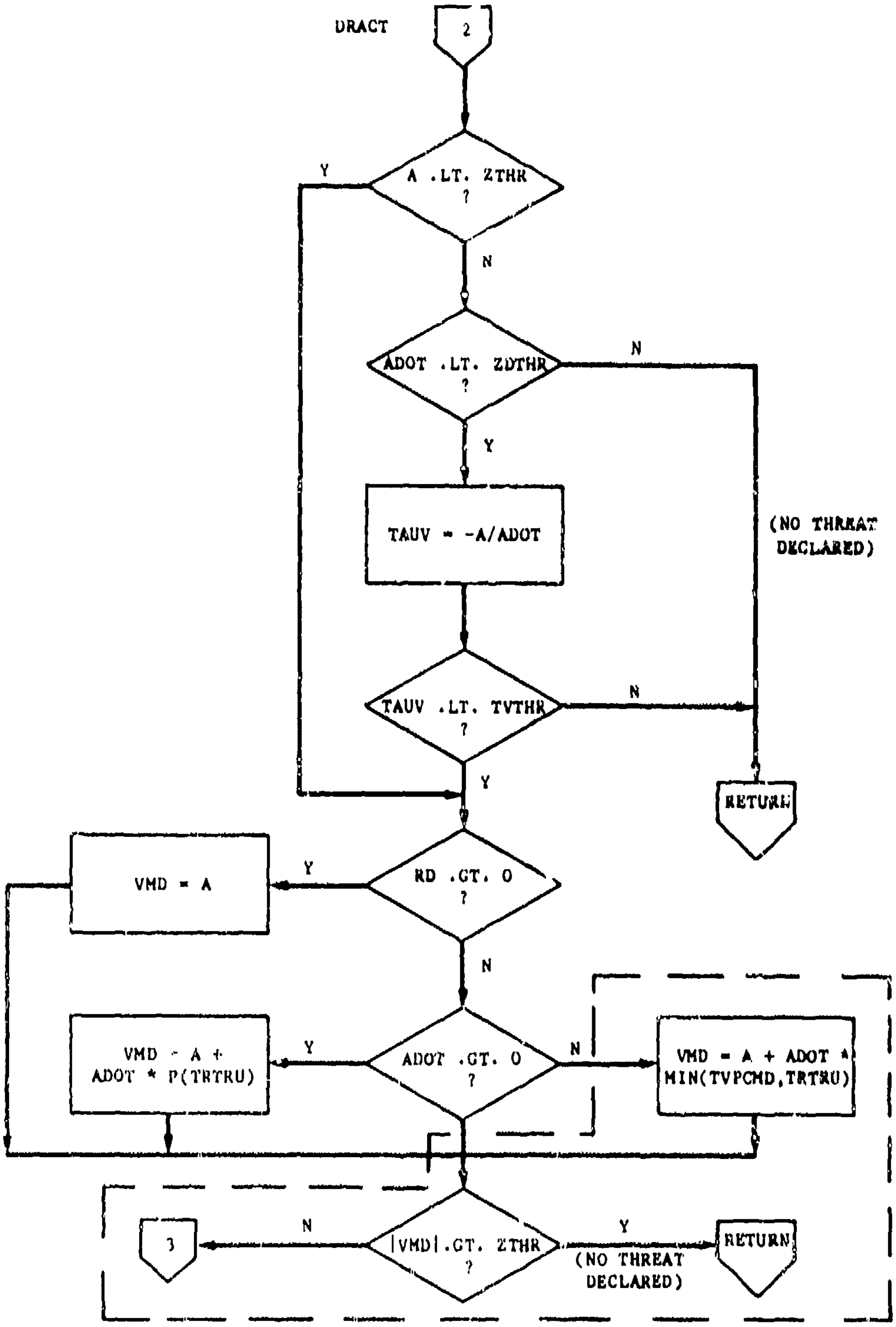


FIGURE 5-1
DETECTION AND RESOLUTION (DRACT) FLOWCHART
(MODIFIED VERSION)

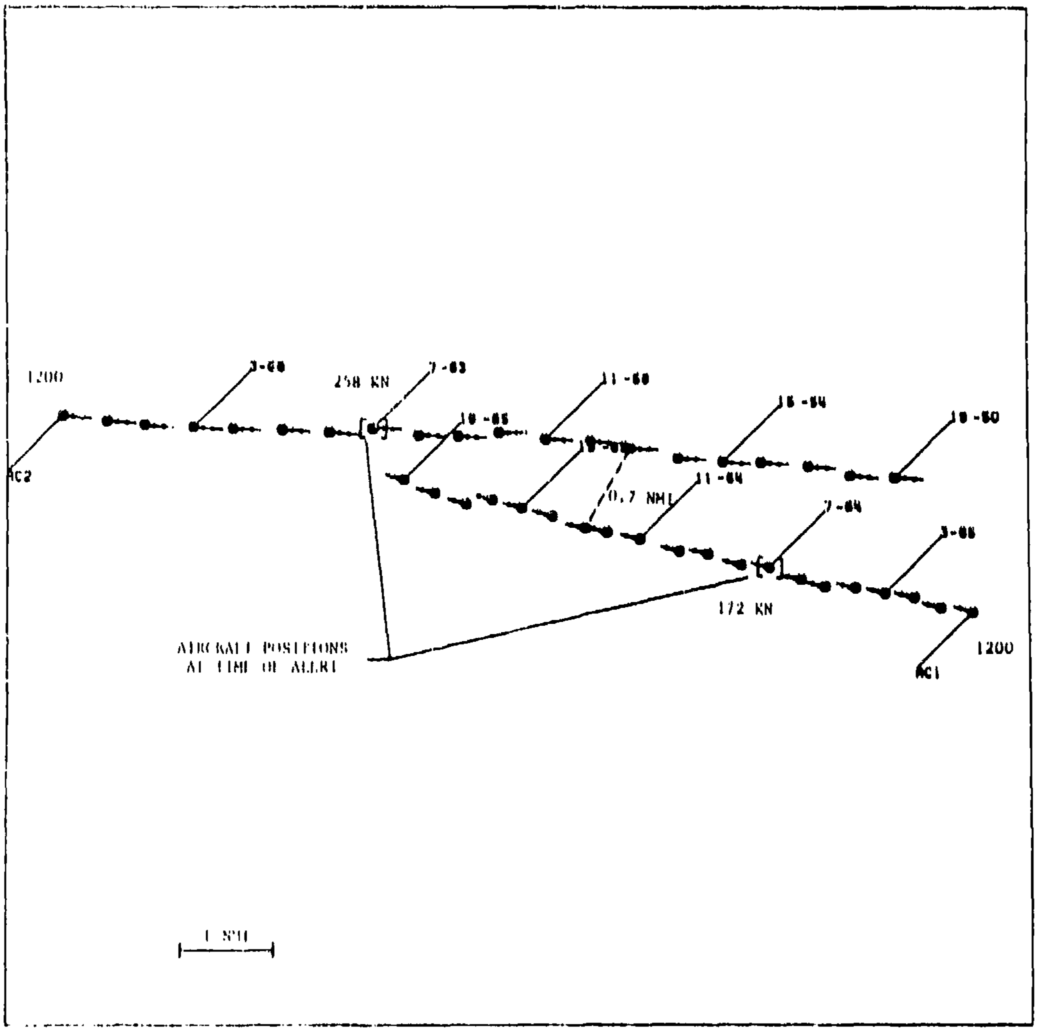


FIGURE 5-2
AN UNNECESSARY POSITIVE ALERT ELIMINATED BY VERTICAL DIVERGENCE LOGIC

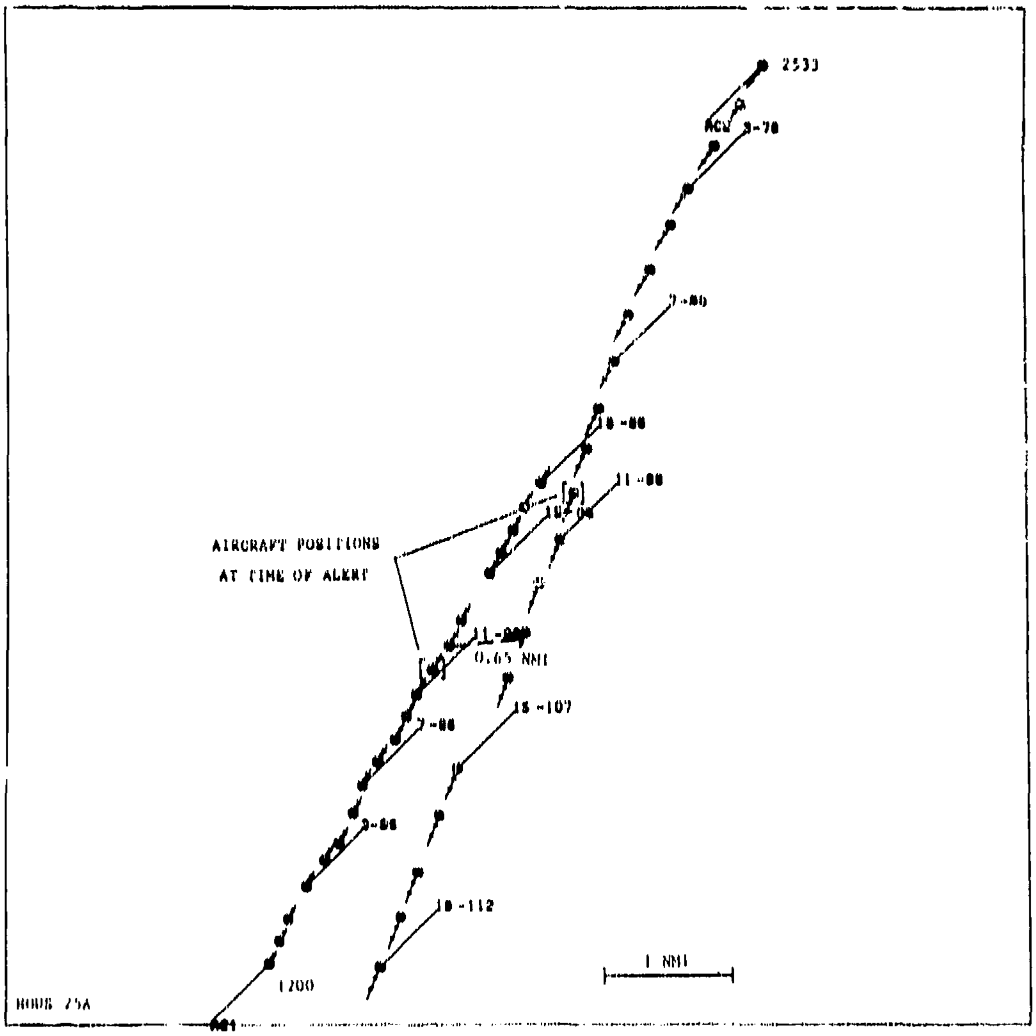


FIGURE 5-3
AN UNNECESSARY POSITIVE ALERT ELIMINATED BY VERTICAL DIVERGENCE LOGIC

with the addition of vertical divergence logic, 52 positive alerts were generated in the performance level 3, 4 and 5 regions. Within the performance level 3 region a 20 second TRTHR value was used, signifying that each intruder is assumed to be not equipped with BCAS.

It is useful to make a comparison of alert rates with and without the vertical divergence logic. The alert rate discussed in Section 3.10 was obtained prior to the addition of the vertical divergence logic. However, an 18 second TRTHR was used in the performance level 3 region to make the data reflect complete BCAS equipage. To determine the quantitative effect of the divergence logic on the alert rate, the 52 alerts described above should be compared to the number of alerts that are generated without divergence logic while using a 20 second TRTHR for consistency. A total of 73 positive alerts were generated without vertical divergence logic using a TRTHR of 20 seconds in performance level 3. Therefore, inclusion of the vertical divergence test in the Active BCAS logic reduces the number of alerts from 73 to 52, a 28% reduction.

5.2 Unequipped Intruder Logic

As a result of ongoing test and evaluation processes for the Active BCAS logic, some modifications have been made to improve performance in specific cases. One such case is the handling of unequipped intruders having vertical rates. Modifications which were made and subsequently reevaluated were found to effectively provide sufficient warning time against such intruders. Figure 5-4 is the flowchart containing modifications made to Figure 2-3(c). The segment of logic involved now performs as follows.

For equipped or near-level unequipped intruders which violate range criteria, a positive alert is generated only when the current altitude separation falls below the specified ALIM threshold. No vertical separation projection is needed. Interim negative alerts will be issued while the altitude separation is below ZTHR but above ALIM in an attempt to slow the vertical rates. While this logic provides adequate protection for equipped or level unequipped intruders, it is necessary to provide additional warning time against an unequipped intruder with a high vertical rate. The scenario depicted in Figure 5-5 illustrates the need for a different logic against these intruders.

Unequipped Aircraft 1 is descending at a rate of 3,000 fpm from an altitude 1,300 feet above Aircraft 2, which is equipped and level. The logic used for equipped intruders would initially

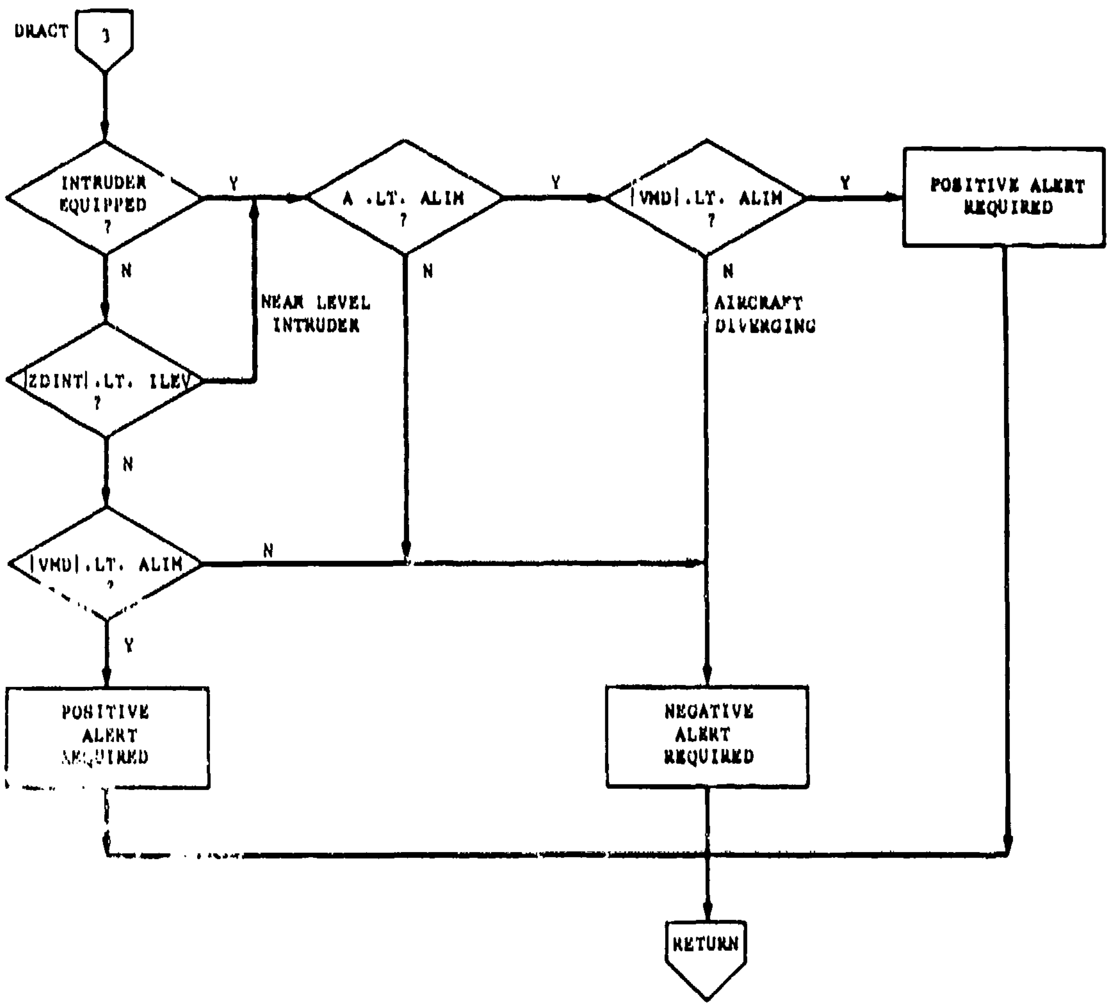


FIGURE 5-4
DETECTION AND RESOLUTION (DRACT) FLOWCHART
(MODIFIED VERSION)

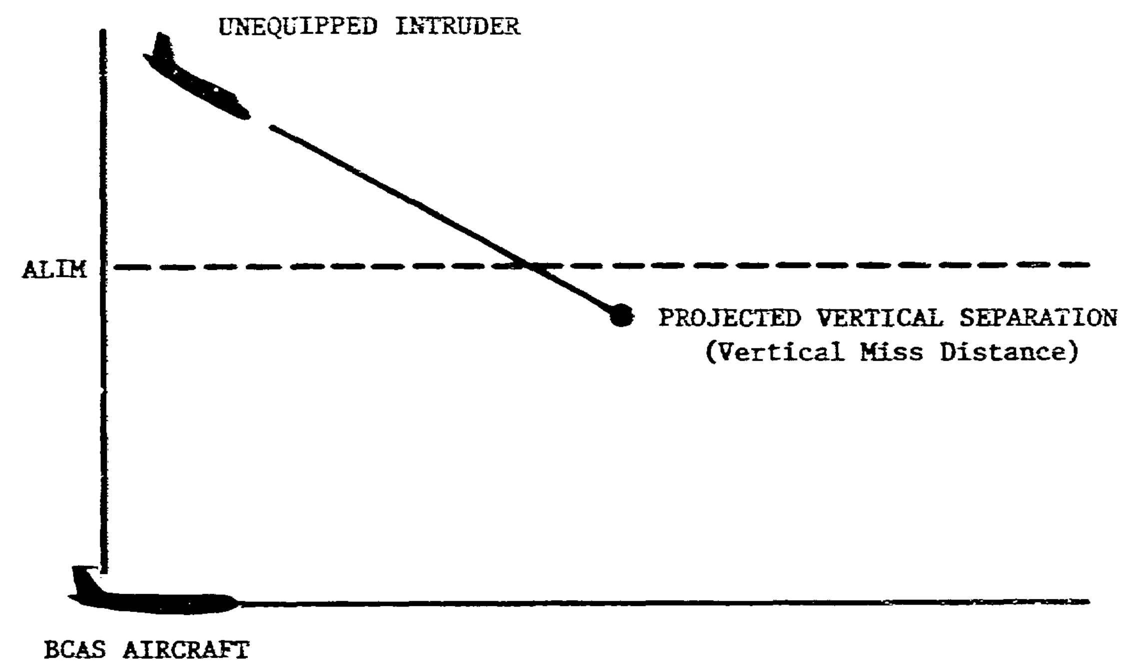


FIGURE 5-5
EXTRA WARNING TIME AGAINST AN UNEQUIPPED INTRUDER WITH A VERTICAL RATE

generate a negative alert to both BCAS equipped aircraft. Normally, the negative alert would result in a level-off by the descending aircraft before that aircraft reached an altitude ALIM feet above the level aircraft. If the descending aircraft were to fall below ALIM then positive alerts would be issued. However, a negative (DON'T CLIMB) alert issued for BCAS Aircraft 2 would not be effective in the unequipped scenario. Aircraft 2 is already level and Aircraft 1 would continue its descent. To use a vertical separation test against the intruder's current altitude in this case would result in insufficient escape time. Aircraft 2 would not receive a DESCEND alert until the intruder was within ALIM feet (340 feet in performance level 3). At this point, there would only be 7 seconds left for the response of the BCAS aircraft to the DESCEND alert.

In order to safeguard against this danger, the BCAS logic utilizes a projected vertical separation calculation. Rather than comparing the current altitude of the intruder against ALIM to determine whether a positive alert is required, the logic looks ahead. The projected vertical separation at the time of closest slant range is tested against ALIM. When it drops below this threshold a positive alert is issued, thereby providing extra escape time for the BCAS aircraft.

5.3 Alert Rate for Unequipped Intruders

The computer runs producing the major results from the Houston data utilized the desensitized parameters and performance level regions specified in Section 3.10 of this document, and included both vertical divergence and unequipped intruder logic updates. Under these conditions, an alert rate of 64 positive alerts in 65 hours of data was produced in the Houston environment. This number reflects the unequipped intruder alert rate, i.e. treating one aircraft in every conflict pair as unequipped.

The additional alert time provided by the unequipped intruder logic is responsible for adding some positive alerts to the Houston results. The number of alerts generated with vertical divergence logic included, but unequipped intruder logic not included, was 52 (refer to Section 5.1). Inclusion of the unequipped intruder logic update increased that number to 64. This increase is deemed necessary in order to provide BCAS equipped aircraft adequate protection against converging unequipped intruders with a high vertical rate.

5.4 Level-Off Scenarios

Providing extra escape time for those conflicts involving an unequipped intruder with a vertical rate brings up the question

of alerting unnecessarily for controller-generated level-off scenarios. It is common ATC practice for a controller to direct an aircraft within controlled airspace to change flight levels, ie., climb or descend to a specified altitude, or to level-off at an intermediate altitude during climb-out or descent. That altitude must maintain a vertical separation of at least 500 feet from any other aircraft. For such scenarios, it was feared that the BCAS logic would generate positive alerts against the intruder prior to level-off, thus disrupting controller management of the airspace. The Houston data base did not confirm this fear. All 12 encounters which were generated solely due to the inclusion of the unequipped intruder logic were individually inspected. Only one was found to have been a level-off scenario. Figure 5-6 shows this example. Aircraft 1 is a level, 1200-code aircraft cruising at 9,600 feet. Aircraft 2 is descending toward Aircraft 1 from an altitude of 11,400 feet at a rate of 3,180 fpm. By scan 10 Aircraft 2 has leveled off at 10,100 feet, exactly 500 feet above the other aircraft. A BCAS positive alert was generated for Aircraft 1 at scan 2, due to the look-ahead prediction that the intruder would be separated from the BCAS aircraft by less than 340 feet within a few scans. At closest approach, scan 7, the two aircraft actually pass with 2,300 feet horizontal and 700 feet vertical separation, a safe distance.

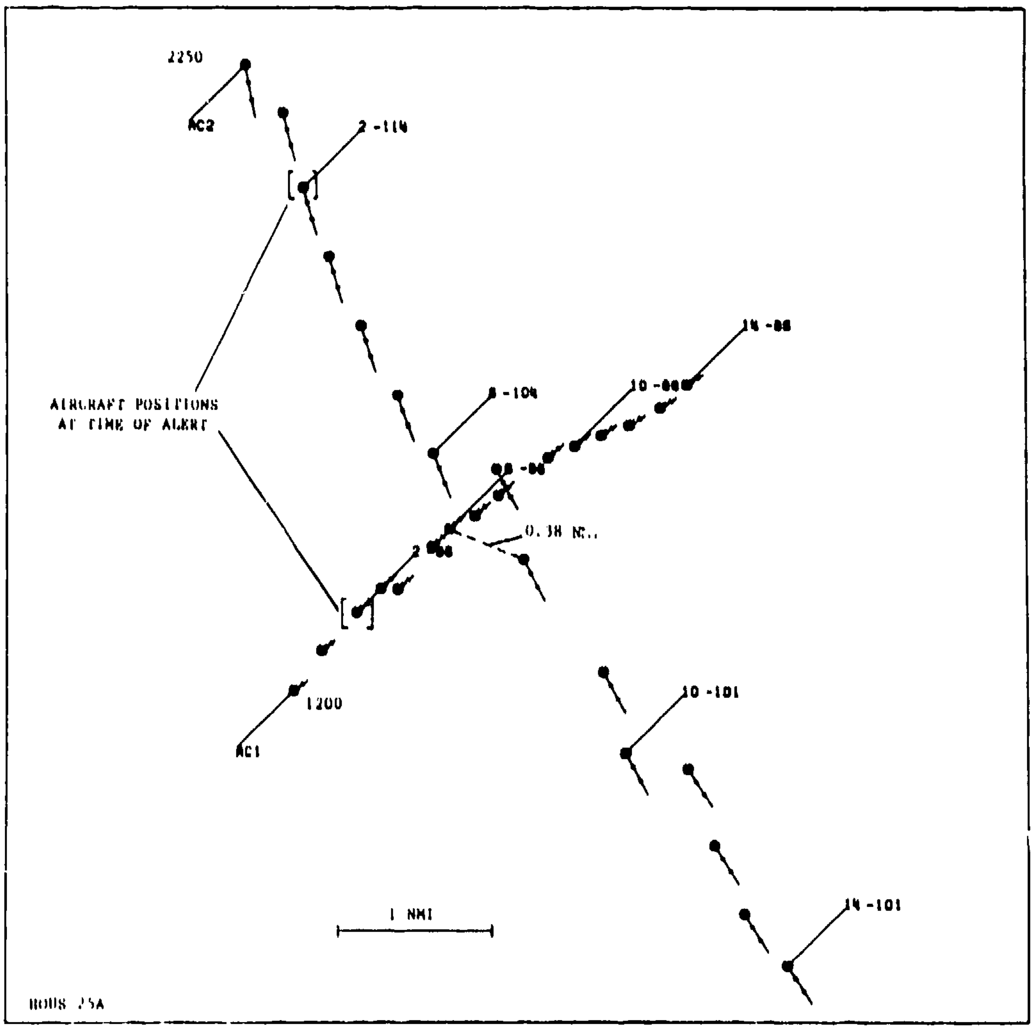


FIGURE 5-6
EXAMPLE OF A LEVEL-OFF SCENARIO

6. PER-AIRCRAFT ALERT RATES

Whereas past studies have emphasized airport alert rates, the Houston data provided the needed data to calculate per-aircraft alert rates. These alert rates are a useful measure of BCAS performance in the terminal area. The method of calculation is as follows.

To compute the alert rate for aircraft of a certain type, the average number of these aircraft present in the 65.02 hours is determined. If a test aircraft were to fly the exact same trajectory as every aircraft of the subject type that was present in the 65.02 hours, the total cumulative flight time and the total number of BCAS alerts experienced could be recorded. When this exercise is completed, the test aircraft will have flown a number of hours equal to 65.02 multiplied by the average number of aircraft of the subject type present. The test aircraft will have experienced a number of alerts equal to twice the number of pairs with alerts where both are of subject type plus the number of pairs with alerts where one is and one is not of subject type. The test aircraft will have received an average of one alert in X hours where X = (65.02 * (average number of aircraft of the subject type present))/(2 * (number of pairs with alerts where both are of subject type) + (number of pairs with alerts where one is and one is not of subject type)). The alert rate so computed will be an average alert rate reflecting the composite experience of all aircraft of the subject type.

Table 6-1 shows the result of using the above formula with data from Table 2-1 and Table 3-3. These alert rates provide an indication of what a pilot can expect as he flies into a terminal environment such as Houston. The per-aircraft alert rate, averaged over all aircraft types, is one alert in 12 hours. For ATC-code aircraft, the rate drops to one alert in 19 hours. It must be emphasized, however that this rate is indicative of flight time in a terminal environment. Because an air carrier aircraft spends only about one third of its flight time in a terminal area, the true rate for such an aircraft over an entire flight will probably be closer to one alert in 60 hours. Appendix D provides a breakdown of the 64 alerts relative to the Houston Intercontinental TCA. The alerts are grouped by performance level and aircraft type. Results show that most of the ATC-code and mixed (ATC/1200) conflicts are generated in the vicinity of Hobby, outside of the TCA.

Another significant fact to be pointed out is the high alert rate for 1200-code aircraft. While the ratio of average instantaneous counts of ATC to 1200-code aircraft was 21 to 3,

TABLE 6-1

HOUSTON TERMINAL AREA
AVERAGE PER-AIRCRAFT POSITIVE ALERT RATE

LOGIC	COMPOSITE FOR ALL AIRCRAFT	RATE FOR ATC CODE AIRCRAFT	RATE FOR 1200 CODE AIRCRAFT
Desensitized Parameters Jan. '80 Logic 64 Alerts	1 Alert In 12 Hours	1 Alert In 19 Hours	1 Alert In 4 Hours

the 1200-code aircraft were responsible for a disproportionately large number of alerts, as indicated by the per-aircraft alert rate of 1 in 4 hours. Specifically, of the 64 positive alerts, 20 conflicts involved only ATC-code aircraft, 12 involved only 1200-code aircraft, and 32 involved one ATC-code and one 1200-code aircraft. Therefore, 44% of the alerts involve 1200-code aircraft. The inclusion of 1200-code aircraft in this study has provided additional insight into terminal environment alert rates.

7. COMPARISON BETWEEN ALERTS GENERATED BY BCAS AND THE TERMINAL CONFLICT ALERT SYSTEM

A comparison of BCAS and the Terminal Conflict Alert System serves two purposes. The first is that since the Conflict Alert System is currently in operation, its effectiveness can be used to benchmark the performance of BCAS. The second is to estimate the impact of BCAS on ATC by measuring the number of BCAS alerts which may occur without ATC notification via Conflict Alert.

7.1 Terminal Conflict Alert System Description

The Conflict Alert System is a ground-radar based system designed with the objective of alerting ATC controllers of potential conflicts in their control area. All controlled aircraft within coverage of the radar for the control ar are within coverage of the Conflict Alert System. Uncontrolled aircraft are not covered.

To track aircraft, the Terminal Conflict Alert System uses range, altitude, and azimuth obtained from the ground radar at a rate of one report each 4.7 seconds. Alerts may be triggered by any one of several mechanisms, embodying current positions, projected positions, and accelerations to determine situations which are potential conflicts. Three different logic modules within the Terminal Conflict Alert System implement these different mechanisms. These algorithms are structured so that the sensitivity of the system can be adjusted depending on the position of the aircraft with respect to the airport.

At Houston the terminal area is divided as shown in Figure 7-1 into several area types. The boundaries of the area types were designed to minimize unnecessary alerts caused by traffic density which normally increases near the airport center and along the approach paths. All of the Conflict Alert System modules are enabled in the Area Type 3, which includes all airspace above 3000 ft as well as regions outside the boundaries of other areas types below 3000 ft. In Area Type 2, the parameters defining a conflict are reduced. Area Type 2 boundaries are located around the approach paths to Houston Intercontinental Airport, William P. Hobby Airport, and Ellington AFB, as well as around David Wayne Hooks Field. In Area Type 1, parameters are further reduced and the module which predicts aircraft position is disabled. Area Type 1 boundaries encompass Hobby and Ellington as one region, and Houston Intercontinental as another.

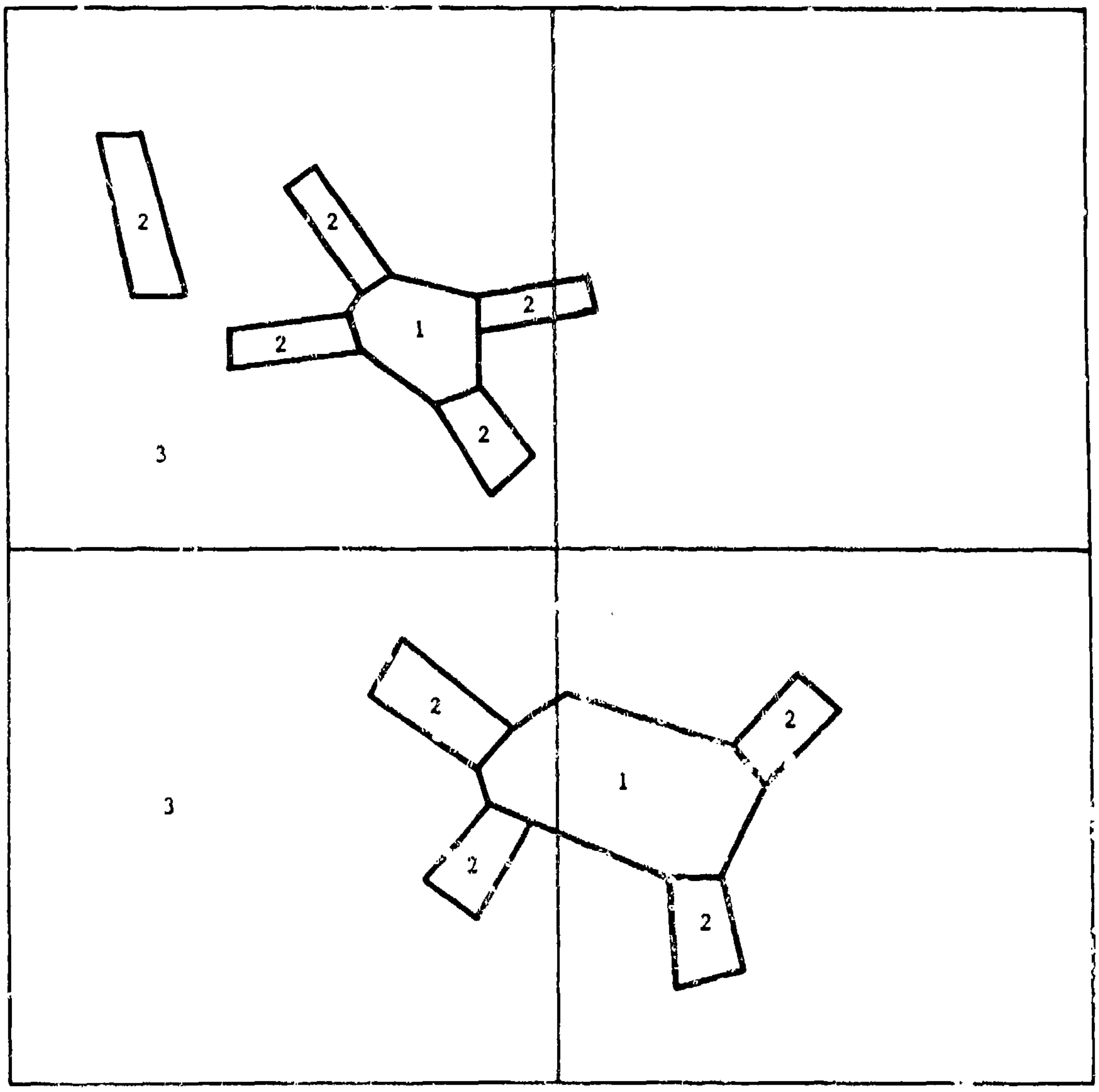


FIGURE 7-1
CONFLICT ALERT MAP AT HOUSTON

The Conflict Alert System generates alerts which consist of flashing symbols on the ATC display associated with the conflicting aircraft. These alerts are meant only to bring attention to potentially dangerous situations. The controller evaluates the indicated potential conflict and determines what (if any) action is warranted. The alert remains on the display until the geometry of the encounter no longer indicates potential conflict.

The parameters used by the Conflict Alert System are designed to provide sufficient advance warning of collision threats so that controller action can be taken to resolve the conflict safely. The Conflict Alert System was designed as an aid to the ATC controller.

7.2 Simulation of the Terminal Conflict Alert System at Houston

The 65 hours of flight data collected at Houston and used in the first part of this report form the basis for comparison between BCAS and the Terminal Conflict Alert System. The Conflict Alert System which is currently operational at Houston had not yet been placed in the field at the time that 10 of the 20 data tapes were collected. Thus, half of this data base is "sterile" from the effects of both BCAS and the Conflict Alert System.

The algorithms of the Terminal Conflict Alert System were coded from Reference 13. It is believed that this code remains an accurate model of the system today since only a few minor changes have been made operational since this coding was done.

The Conflict Alert System coding used for this study does permit operation at each of the protection levels appropriate to the three Area Types. However, it does not include a capability to do Area Type mapping. Therefore, the entire 65 hours of Houston data was executed at each of the three protection levels. The first occurrence of an alert for each encounter at each protection level was saved, and sorted by Area Type based on the midpoint between aircraft at the time of the alert. All alerts which occurred in the wrong Area Type for the protection level being executed were eliminated.

This Area Type mapping approximates but does not duplicate the operational algorithms. The major difference is that the operational program determines Area Type (and thus protection level) for individual aircraft and selects the Area Type for evaluating the encounter depending on which Area Types are

involved for the two subject aircraft. Use of the encounter midpoint tends to limit the "movement" of the encounter across Area Type boundaries.

The results of the Conflict Alert System executions are shown in Figure 7-2. This figure combines the sorted data output onto one Houston Area Type map. In general, the Conflict Alert System does not "see" uncontrolled (1200-code) aircraft. Therefore, Figure 7-2 is the result of removing all 1200-code aircraft from the data, and most accurately portrays the Conflict Alert System now in operation. The Conflict Alert System generated alerts for 95 encounters not involving 1200-code aircraft in 65 hours.

The figure presented is based on computer-generated output and graphically represents the numeric data results. The geometry of the figures is distorted by the limitations of the output device. Also, data points may overlay one another, making exact counts impossible from the figures alone. Within these limitations, the figures do illustrate the simulation results.

The Houston Area Type map boundaries are formed by straight lines connecting the boundary marking points. Each data point on the figure represents the midpoint of an alert. The figure is limited to 25 miles North, South, East and West of a position from the center, and all data beyond the 25 mile limit is placed on the figure border.

The numeric data output identifies both aircraft, time of the alert, and gives all positional data at the time of the alert. Further detail was obtained by using aircraft identification and time to reference the data base directly.

7.3 Use of Simulated BCAS Data

The same simulation of the BCAS logic used for obtaining the results in previous sections of this report was used to compare results with Terminal Conflict Alert. Both simulations operate on the data base extracted from ARTS III data tapes, such that direct comparison of simulated results is possible. The output of the BCAS simulation is formatted identically to the output of the Conflict Alert System simulation, which allows use of identical post-simulation data reduction programs. The BCAS simulation is also capable of executing at any of the BCAS performance levels, but, like the Conflict Alert Simulation, does not include any capability to impose boundaries on the areas for which each performance level might be used.

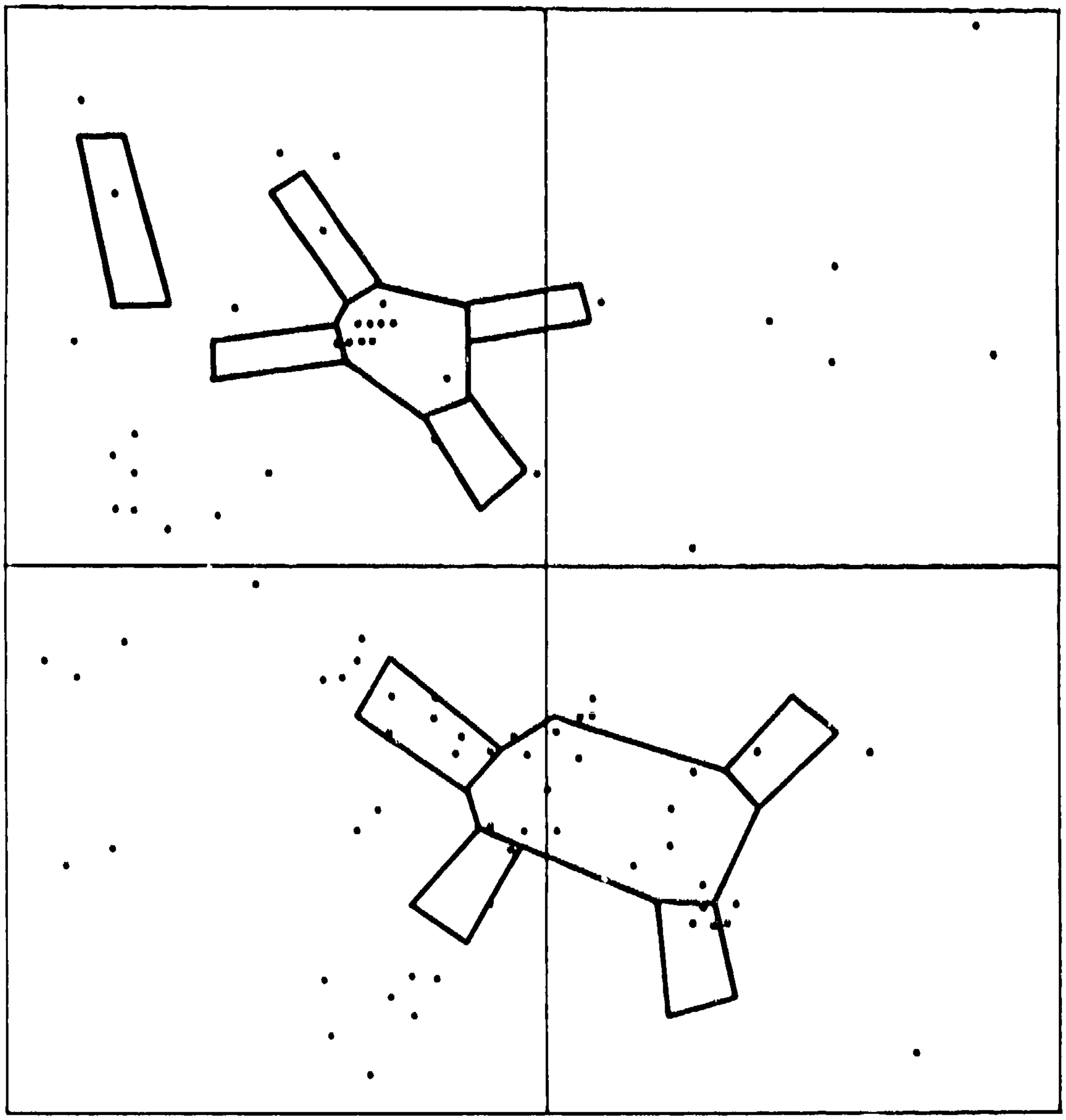


FIGURE 7-2
LOCATION OF CONFLICT ALERT SYSTEM ALERTS AT HOUSTON AREA AIRPORTS

Since BCAS performance levels are determined by range and altitude, a separate routine was built to sort and correlate alerts by performance level. The sorting routine assumed the placement of three RBX's, one at the center of the runways at each of the three largest airports (Houston, Hobby and Ellington). Within 900 ft altitude and 2 nmi range of an RBX, BCAS alerts are disabled. Outside of these areas, but within 10,000 ft altitude and 10 nmi range, BCAS is simulated to be operating at performance level 3 (TRTHR = 20sec, DMOD = 0.1 nmi, ALIM = 340 ft). In all other airspace below 10,000 ft, BCAS is simulated at performance level 4 (TRTHR = 25sec, DMOD = 0.3 nmi, ALIM = 340 ft), and above 10,000 ft BCAS is simulated in performance level 5 (TRTHR = 30sec, DMOD = 1.0 nmi, ALIM = 440, 640 or 740 ft). These performance level boundaries are shown overlaid on the Houston Terminal Area Conflict Alert Map in Figure 7-3.

Only positive BCAS alerts were used for the comparison with Terminal Conflict Alert System alerts. Furthermore, the comparison is made only for encounters that involve no 1200-code aircraft. While alert rates with 1200-code aircraft would be the most significant in studying BCAS alerts alone, the Terminal Conflict Alert system does not deal with uncontrolled (1200-code) aircraft, and a comparison using encounters with 1200-code aircraft would not be representative of real-world experience.

After sorting and correlating simulated BCAS alerts to obtain a composite set of alerts at each appropriate BCAS performance level, the BCAS data was located on the Conflict Alert map to yield a pictoral comparison. These results are shown in Figure 7-4. BCAS generated positive alerts involving only ATC-code aircraft in 20 encounters in 65 hours.

The Conflict Alert System data and the BCAS data are tagged with both time of alert and source (Conflict Alert or BCAS). The two data files were combined and sorted by aircraft identification, such that all encounters which resulted in both Conflict Alert System alerts and BCAS alerts could be readily observed and compared. A brief data reduction program was written to output comparative data on the alerts.

7.4 Analysis of Comparative Performance

It is clear from the pictorial illustrations of the BCAS alerts and the Conflict Alert System alerts that the BCAS alert rate is much lower. There are two obvious reasons why this should be true. The first is that BCAS alerts are disabled in the region of highest alert density. The second is that the Conflict Alert

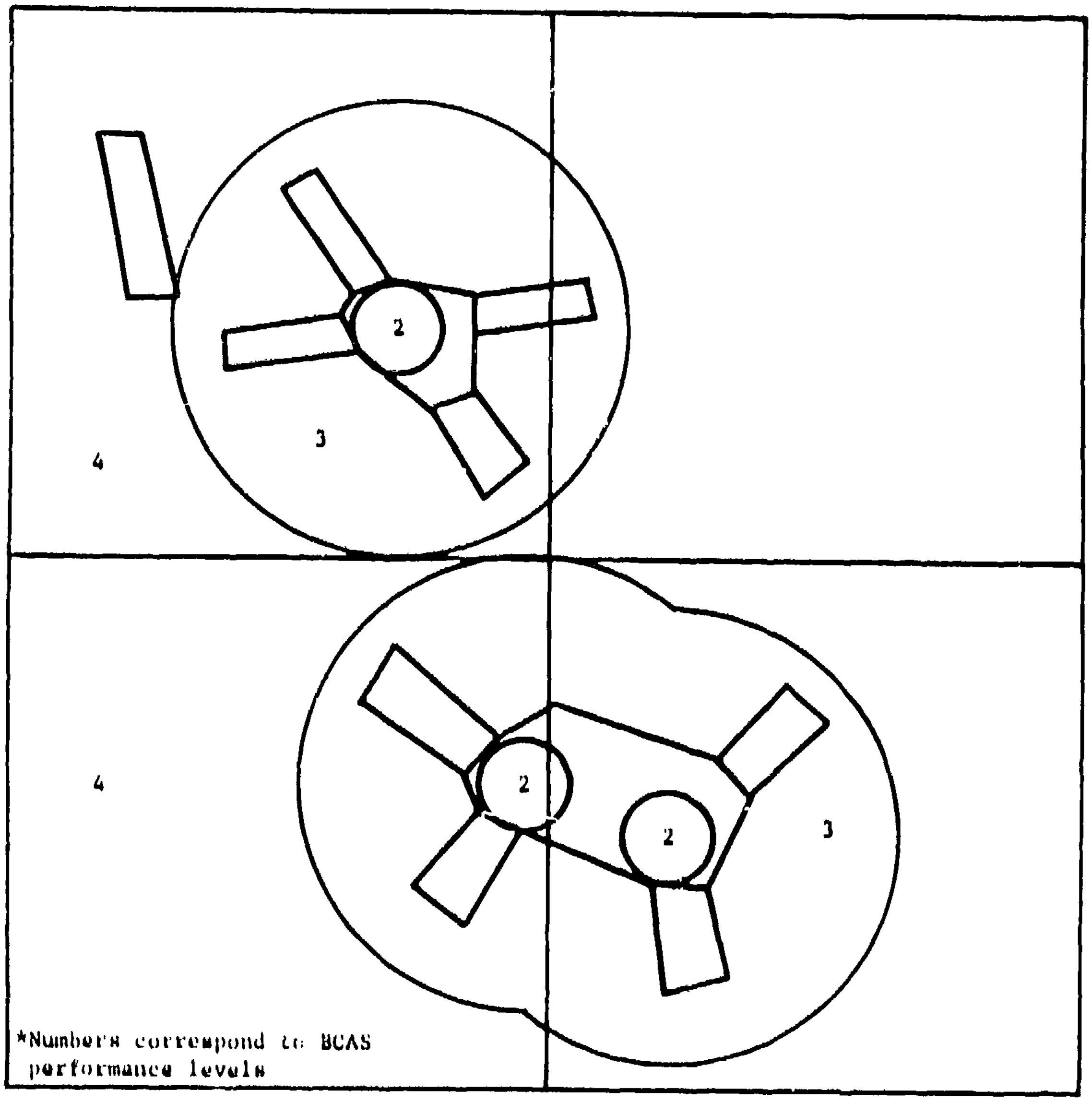


FIGURE 7-3
OVERLAID BCAS AND CONFLICT ALERT MAPS

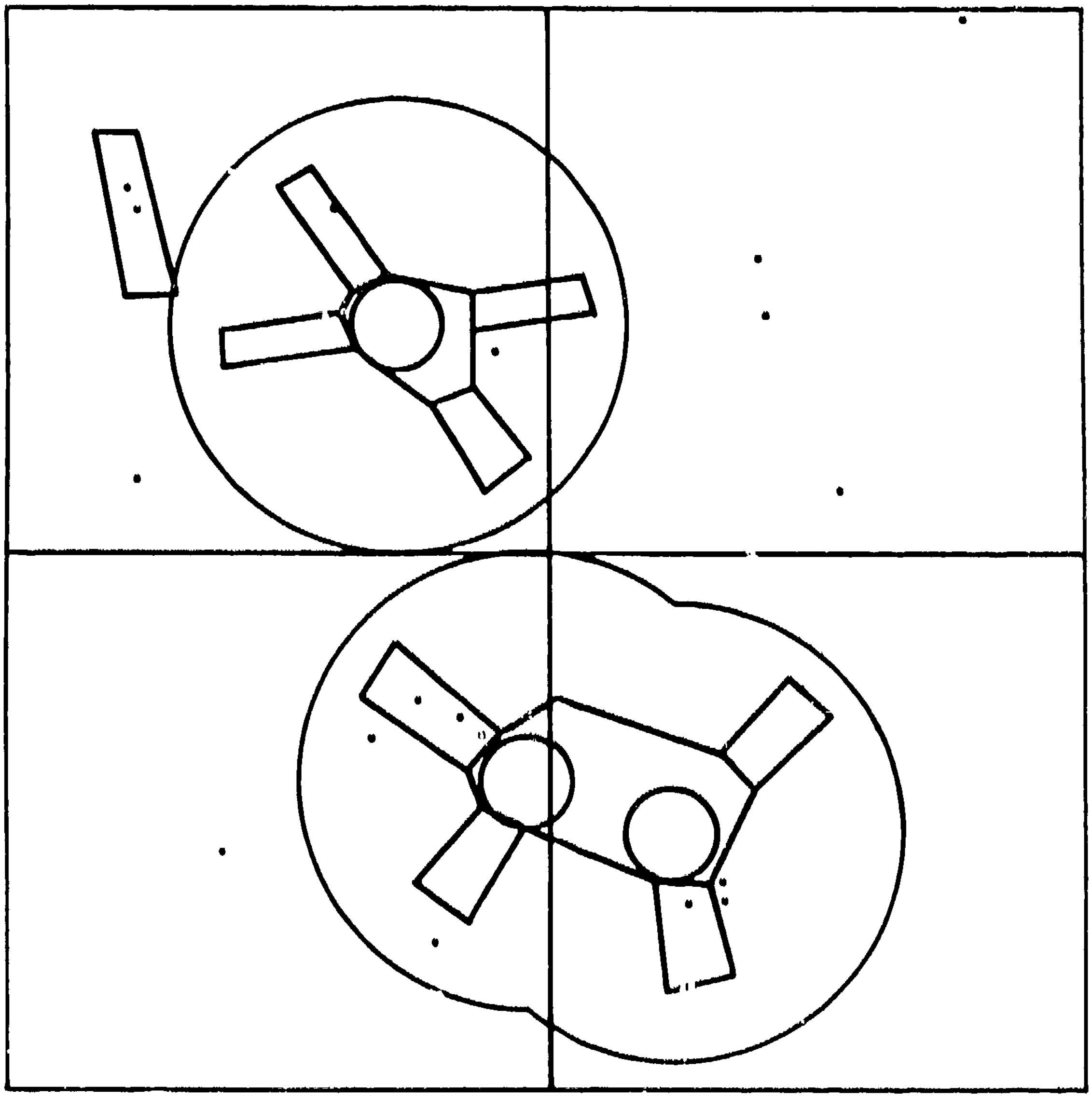


FIGURE 7-4
LOCATION OF BCAS ALERTS AT HOUSTON AIRPORTS
(WITHOUT 1200-CODE AIRCRAFT)

System, designed to direct controllers' attention to potential hazards, provides larger protection volumes than does BCAS, which is designed to provide last minute collision avoidance service.

In view of the latter, and the concern that air traffic control may be disrupted if controllers on the ground are not forewarned of BCAS-initiated maneuvers, the comparative analysis of BCAS and the Conflict Alert System is centered on those BCAS alerts which occur before or without a corresponding Conflict Alert System alert.

A summary of the comparison between BCAS and the Conflict Alert System is shown in Figure 7-5. It will be referred to in the sections that follow.

7.4.1 Correspondence of Alerts

Of the 96 total encounters which generated alerts in the simulations of either BCAS or the Terminal Conflict Alert System, only 19 generated alerts under both systems. The Conflict Alert System found alert-generating encounters 76 times when BCAS did not. In only one encounter did BCAS generate an alert when Terminal Conflict Alert did not.

In the 19 encounters in which both systems alerted, Conflict Alert usually alerted earlier (by up to 42 seconds). In three cases, BCAS alerted earlier (by up to 10 seconds).

The Conflict Alert System, with its greater sensitivity, will normally detect a conflict earlier than BCAS if the flight paths of the two aircraft are fairly stable. The maximum look-ahead time used by the Conflict Alert System is 40 seconds, whereas BCAS is limited to 30 seconds. The Conflict Alert System defines the range threshold as high as 1.2 nmi, whereas BCAS uses a maximum of 1 nmi. These two parameters alone could result in as much as 130 seconds extra "lead-time" by the Conflict Alert System for encounters with a (minimum) closing rate of 6 knots.

If one or both of the aircraft are performing maneuvers, or are acquired late by the radar (and tracker), the encounter may very quickly satisfy both BCAS and Conflict Alert System threat-defining thresholds. In such cases, BCAS benefits from a one-second scan rate and its declaration of a threat after 2 hits, whereas the Conflict Alert System relies on a scan rate of 4.7 seconds and requires three hits on a target (in certain of the alert-generating logic modules) before declaring it a

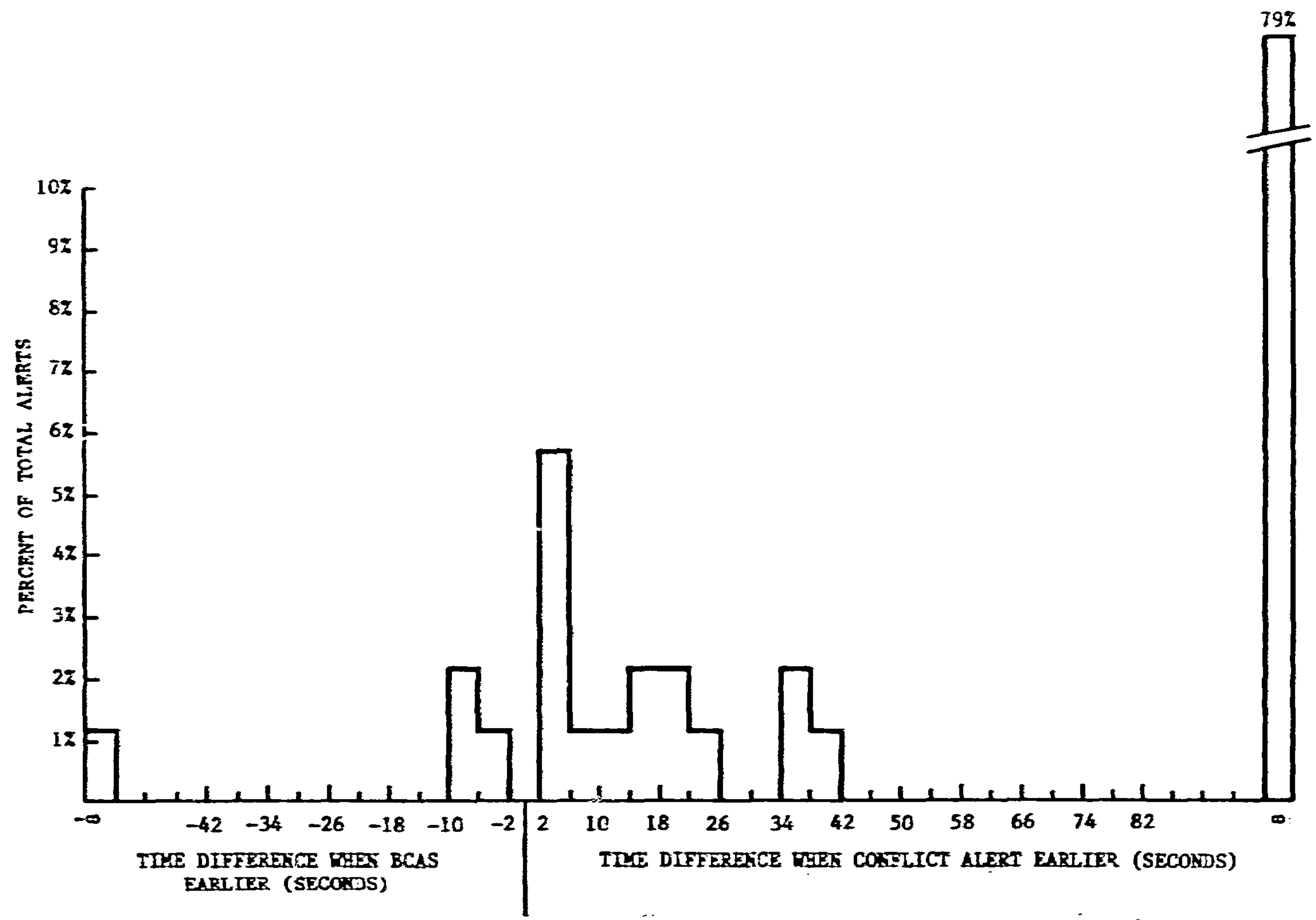


FIGURE 7-5
COMPARISON OF TIME DIFFERENCE BETWEEN ALERTS GENERATED BY BCAS AND CONFLICT ALERT

threat. Because the available data was recorded at a 4.7 second scan rate, the BCAS simulation was modified to accept a threat on only one hit. Thus, an encounter which generates a "hit" in both systems at the same time will be declared as a threat immediately in the BCAS simulation, but will be delayed at least 2 more scans (almost 10 seconds) before being declared a threat in the Conflict Alert System. If for any reason the encounter did not result in three consecutive "hits" by the Conflict Alert System, additional delay would be added.

7.4.2 Explanation for the BCAS-Only Alert

Only one track pair in 65 hours of data produced a BCAS alert without an accompanying Conflict Alert System alert. Examination of the track pair revealed that at the scan prior to the BCAS alert, the data experienced garble effects. Immediately following the alert, a data gap appears which lasts for approximately 10 scans.

Figure 7-6 shows a sequential series of horizontal plots of this encounter. The encounter begins with the aircraft separated by 3.8 nmi in range and 1700 feet in altitude. Both aircraft are descending on a collision path. By scan 16, the aircraft are still converging, separated by 1 nmi and nearly 1100 feet. At scan 25, the BCAS unequipped intruder logic generates a positive alert. Although the aircraft are separated by 640 feet, they are predicted to be within the ALIM threshold in less than 25 seconds. Immediately following the alert, 10 scans of data are missing. When the track resumes, the aircraft have begun to diverge in range, and Aircraft 2, which had been in trail during the entire encounter, has overtaken Aircraft 1. By scan 49, the two aircraft are co-altitude, in trail, and separated by 3 nmi.

The Conflict Alert module which was simulated to be in operation in the Area Type in which this alert occurred requires that the horizontal and vertical envelopes around an aircraft pair overlap at predicted closest approach in order to produce an alert. At closest approach in range, the aircraft were 780 feet apart while the altitude separation was in excess of 640 feet. Therefore, no alert was given. The BCAS logic, with the extra warning time logic against unequipped intruders with a vertical rate, predicted a conflict for 2 scans before the intruder began its turn and the data drop occurred.

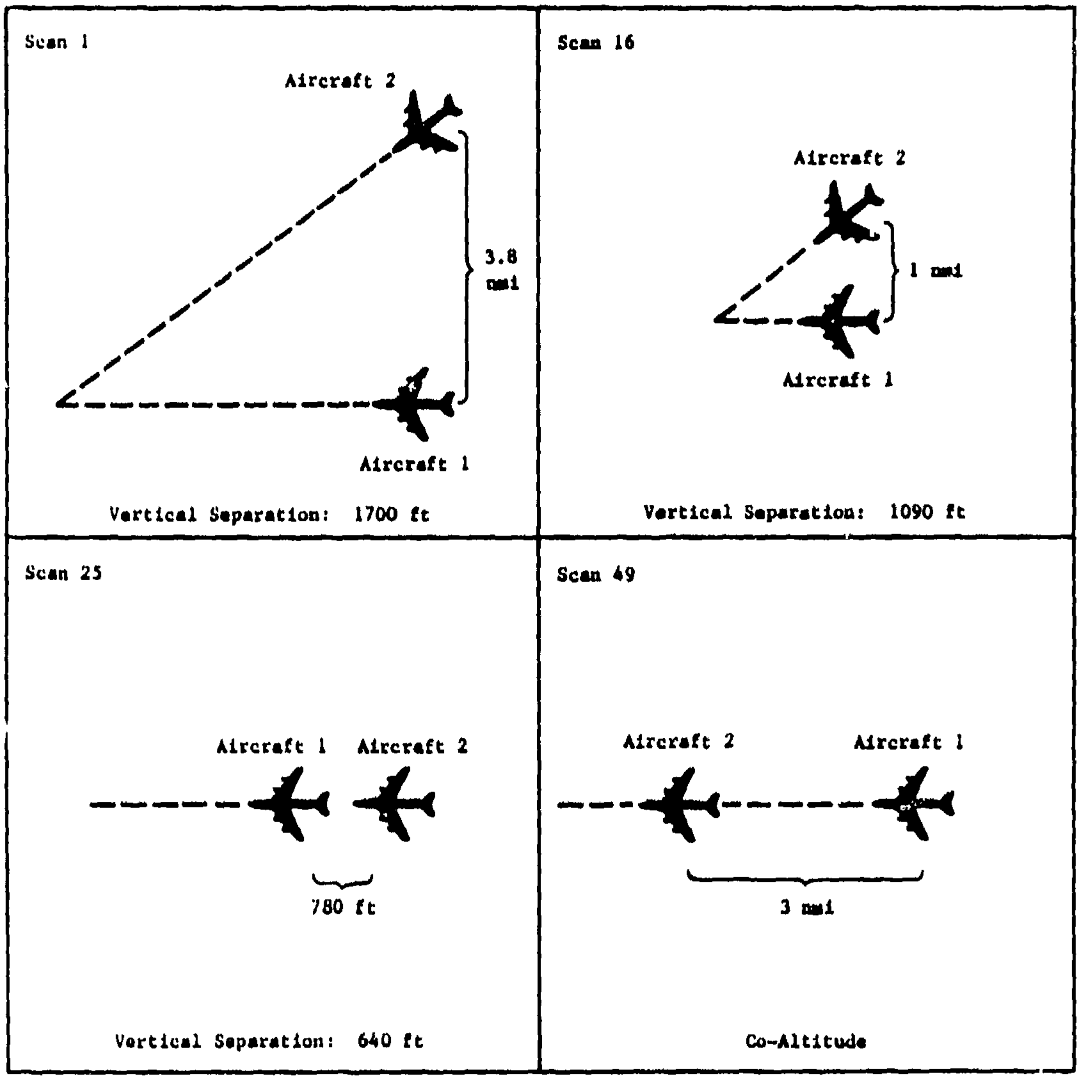


FIGURE 7-6
ENCOUNTER WHICH PRODUCED A BCAS ALERT WITHOUT A CONFLICT ALERT SYSTEM ALERT

7.4.3 Explanation for the Three Encounters in Which BCAS Alerted Earlier

Three track pairs in 65 hours produced a BCAS alert earlier than a Conflict Alert System alert. Two of the conflict pairs were already within alert thresholds at the first scan of printed output. Therefore, BCAS alerted on the first scan, while Conflict Alert was delayed by 2 scans due to its 3 out of 5 logic.

The third conflict occurred in what would have been the Conflict Alert Area Type 1. Only a proximity logic is in effect in this area. Its thresholds are 0.75 nmi in range and 275 feet in altitude separation. The equivalent BCAS altitude threshold in this area is 340 feet. The proximity logic, with its smaller detection parameters, generated an alert 2 scans after the BCAS logic declared an alert.

None of these early BCAS alerts occurred more than 2 scans prior to the Conflict Alert System alert. Therefore, BCAS alerts would not appear to impact the Conflict Alert System.

7.5 Summary of BCAS and Conflict Alert Comparison

In the 65 hours of Houston data there were 96 encounters involving only ATC-code aircraft that generated either a Terminal Conflict Alert System alert or a BCAS positive alert. Seventy-six encounters produced a Conflict Alert System alert but no BCAS alert. One encounter produced a BCAS alert but no Conflict Alert System alert. On the 19 encounters which produced both a BCAS and a Conflict Alert System alert, BCAS alerted earlier in three encounters. In these three encounters BCAS alerted earlier by at most 10 seconds (2 scans).

These results show that the Terminal Conflict Alert System alerts much more frequently than BCAS for encounters involving only ATC-code aircraft. Conflict Alert gives 95 total alerts in 65 hours for ATC-code aircraft, while BCAS gives 20 positive alerts in 65 hours for ATC-code aircraft. BCAS also gives alerts to BCAS-equipped aircraft due to 1200-code intruders. The BCAS logic itself would give 64 positive alerts in 65 hours for all encounters regardless of beacon code status of the aircraft, if one aircraft were equipped and the other were not equipped in each encounter. How many total BCAS alerts would be given in the Houston environment is difficult to estimate, because it depends on how many and what types of aircraft would be BCAS equipped.

These results indicate that it is unlikely that BCAS will alert on an encounter involving two ATC-code aircraft when the controller has not already been notified by a Conflict Alert warning. However, BCAS may generate alerts routinely to controlled aircraft against 1200-code aircraft without the controller having been notified.

8. ANALYSIS OF BCAS PROTECTION

An analysis of the Houston area alert rate and the role of desensitization is not complete without studying the possible tradeoffs in separation protection. Measures of the separation provided by BCAS generated advisories were obtained using the fast-time simulation capability of the Monte Carlo Simulation Program. This program simulates aircraft motion along collision flight paths and can simulate aircraft response to collision avoidance commands. It contains the Active BCAS logic for detection and resolution. The Monte Carlo method provides a means of generating a large number of randomly distributed aircraft encounters from a small input data base. The data base used in this protection analysis consisted of 15 actual midair collisions reconstructed from the National Transportation Safety Board reports of each accident. This data is very significant because, like the Houston ARTS data, it is real-world data. In order to understand the full impact of desensitization, BCAS performance was analyzed to determine whether or not sufficient separation could have been provided with desensitized parameters to prevent the accidents.

Several runs of the midair data were made. The 15 scenarios were first categorized by performance level. The performance level boundaries shown in Figure 3-11 which were used at the Houston airports were assumed to exist at the 200 airports which were selected for RBX placement in the RBX study described in Appendix A. According to the range from the airport and altitude of the aircraft at the moment of collision, each midair was assigned the performance level which would have been applied had the scheme been in operation at each RBX location. The midairs were assigned the performance level appropriate to the nearest RBX.

As a result of this categorization, six of the fifteen midairs occurred in what would have been the performance level 3 region. Five midairs occurred in the performance level 4 region. Three others occurred in performance level 5. One of the midairs, St. Louis, occurred within 1.5 nmi of the end of Runway 17 at Lambert Field, an area in which BCAS advisories would probably have been disabled. Using the performance level regions of Figure 3-11, the St. Louis midair collision could not have been prevented by commands issued by the BCAS logic. However, this midair scenario was simulated in one run using the performance level 3 parameters and thresholds in order to assess the effectiveness of the BCAS command logic had the collision occurred within an active region of airspace. Results of the simulation will be presented in parallel with the performance level 3 scenario results.

It is possible that BCAS-generated traffic advisories would be generated by the BCAS system in regions such as this close to an airport where commands are inhibited. It is not possible to determine whether or not traffic advisories from BCAS would have been able to prevent this midair collision.

A description of each of the simulation runs appears in Table 8-1. The midairs were simulated first with the parameter values and thresholds appropriate to the performance level region of each midair. Simulations were also run for each group of midairs using a performance level other than the nominal one selected as a result of the mapping scheme. This was done in order to weigh the tradeoffs in separation protection when parameter values of the next higher or next lower performance level are used. In addition, this comparison aided in determining whether or not the performance level mapping scheme selected as a result of the Houston data analysis could be effective at other airports. The flexibility also exists in the Monte Carlo Simulation Program to allow protection comparisons to be made for such factors as pilot delay time, aircraft escape rates, and altimetry errors. Additional runs were also made to show the effects of these variations.

The input data column in the table refers to the three sets of scenarios, categorized by performance level 3, 4 or 5. The performance level index column indicates which set of performance level thresholds were used for a particular set of scenarios. The Monte Carlo trials were first run for each scenario assuming that both aircraft were BCAS equipped. Next, the scenarios were run assuming that only one aircraft was equipped with BCAS. In order to make a thorough assessment of the unequipped runs, each scenario was simulated first with one aircraft equipped, and then the scenario was reversed and the other aircraft was simulated to be equipped. In the unequipped runs therefore, each scenario was simulated twice.

8.1 The Midair Collision Data

The 15 midair collisions used in this analysis were chosen because they were the only accidents during the period 1965 through 1978 whose flight paths could be adequately reconstructed from the National Transportation Safety Board accident report data. Other midair collisions occurred during the time covered by these 15, but sufficient data did not exist to permit these to be included in this study. Figure 8-1 represents the actual plan view of the midair geometries grouped by performance level region. Each scenario description includes

TABLE 8-1

MONTE CARLO SIMULATION RUNS

Input	Equippage	Performance Level Index	Simulation Characteristic
Performance Level 3 Scenarios	Both Equipped	Performance Level 3	Error-Free Environment
Performance Level 4 Scenarios	Both Equipped	Performance Level 4	Error-Free Environment
Performance Level 5 Scenarios	Both Equipped	Performance Level 5	Error-Free Environment
St. Louis Scenario	Both Equipped	Performance Level 3	Error-Free Environment
Performance Level 3 Scenarios	Both Equipped	Performance Level 3	Nominal
Performance Level 4 Scenarios	Both Equipped	Performance Level 4	Nominal
Performance Level 5 Scenarios	Both Equipped	Performance Level 5	Nominal
Performance Level 3 Scenarios	One Unequipped	Performance Level 3	Nominal
Performance Level 4 Scenarios	One Unequipped	Performance Level 4	Nominal
Performance Level 5 Scenarios	One Unequipped	Performance Level 5	Nominal
St. Louis Scenario	One Unequipped	Performance Level 3	Nominal
Performance Level 3 Scenarios	One Unequipped	Performance Level 3	No Response Deviations
Performance Level 3 Scenarios	One Unequipped	Performance Level 3	Perfect Tracking
Performance Level 3 Scenarios	One Unequipped	Performance Level 3	No Altimetry Error
Performance Level 3 Scenarios	One Unequipped	Performance Level 4	Nominal
Performance Level 4 Scenarios	One Unequipped	Performance Level 3	Nominal
Performance Level 5 Scenarios	One Unequipped	Performance Level 4	Nominal
Performance Level 3 Scenarios	One Unequipped	Performance Level 3	Increased Response
Performance Level 3 Scenarios	One Unequipped	Performance Level 3	10 Second Response
Performance Level 4 Scenarios	One Unequipped	Performance Level 4	10 Second Response
Performance Level 5 Scenarios	One Unequipped	Performance Level 5	10 Second Response

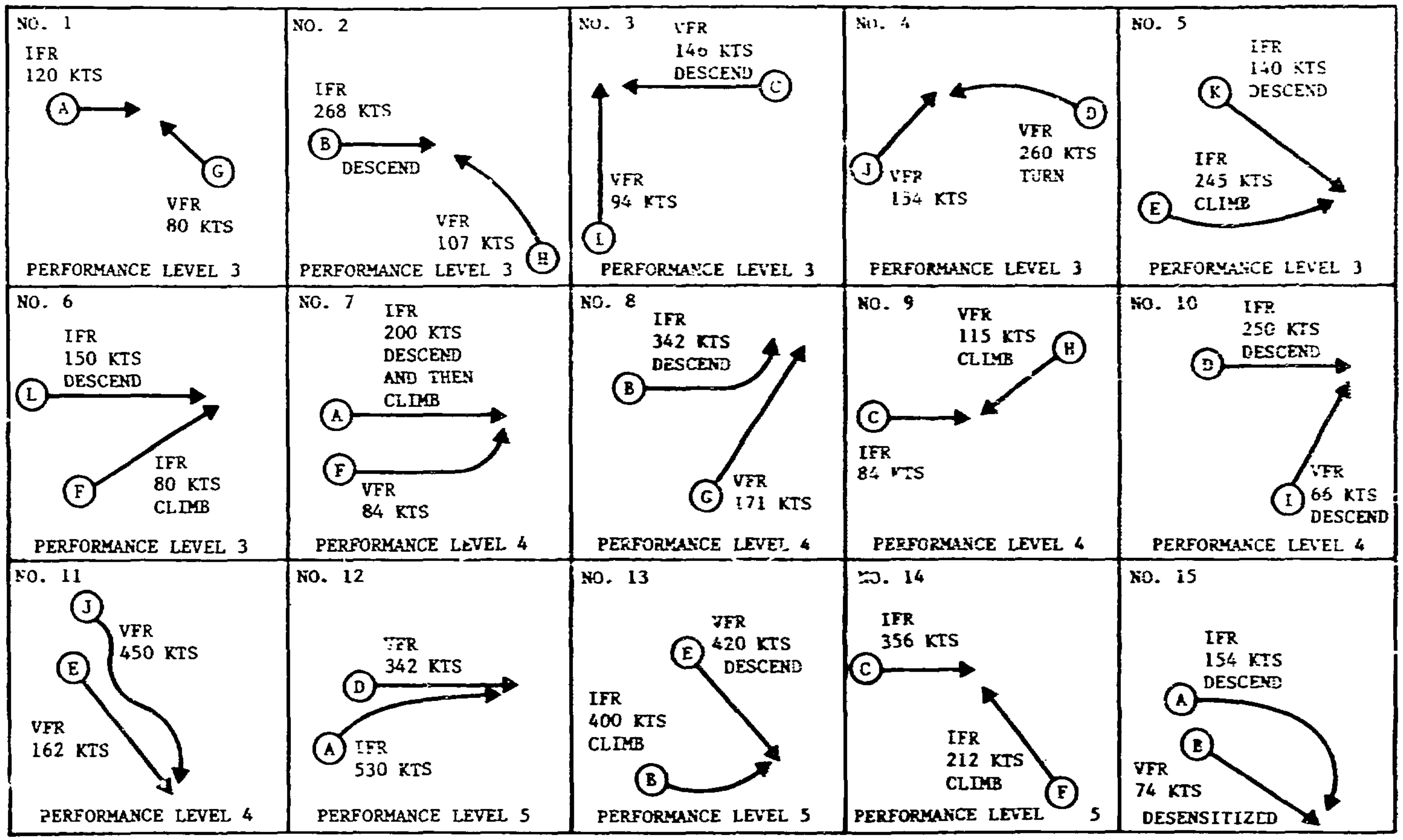


FIGURE 8-1
THE 15 MIDAIR COLLISION GEOMETRIES

the speeds of the aircraft, whether the aircraft were flying IFR or VFR and a designation of any vertical maneuvers initiated during the encounters. The letters assigned to each aircraft correspond to those found in the scatter plots described in the following sections. For runs simulating both aircraft as BCAS equipped, the letter nearest the beginning of the alphabet is used to represent that scenario on the scatter plot for the appropriate performance level. For example, scenario 1 would appear as the letter 'A' on a scatter plot for an equipped run in performance level 3. For runs simulating one equipped and one unequipped aircraft, the letter used to represent each scenario is the letter corresponding to the equipped aircraft. Therefore, on a scatter plot for an unequipped run in performance level 3, the data point 'A' represents scenario 1 when aircraft 'A' is equipped. Data point 'G' represents the inverse of the scenario, that is, the same collision geometry is used but the other aircraft, aircraft 'G', is BCAS equipped.

Appendix C contains a more detailed description of the midair collisions, such as their location, altitudes, and the type of aircraft involved.

8.2 Monte Carlo Simulation Program

The computer simulation program called the Monte Carlo Simulation for Collision Avoidance Systems (MCSCAS) was developed to simulate the flight environment for the purpose of evaluation and analysis of collision avoidance systems. The Monte Carlo Simulation Program provides simulation flexibility so that performance evaluation and sensitivity analysis, etc., can be done on collision avoidance systems.

The Monte Carlo Simulation Program simulates the "external" flight environment of up to 4 aircraft for the BCAS logic to work on. For this analysis, the geometries of 15 actual midair collisions were input for simulation. The flight environment includes the aircraft kinematics which are specified by the vertical and horizontal trajectories; the tracking, transponder, and altimetry models; and the pilot and aircraft response models.

The simulation program realizes the random nature of the real world by generating both a large number of randomly distributed aircraft encounter situations and randomly distributed measurement and response errors for the simulation.

The nominal flight trajectories of both aircraft in a scenario are specified by the initial position and velocity vectors of the aircraft and up to four sets of time sequenced horizontal

and/or vertical maneuvers for each aircraft. Figure 8-2 is an example of an input scenario and shows the relationship between that scenario and the jittered encounters which appear on an output scatter plot. The top figure is the horizontal plot of a real collision course. The bottom plot shows how the initial scenario conditions are jittered to provide scatter for the 20 encounter repetitions. This form of plot illustrates the closest point of approach for multiple scenarios and multiple runs, plotting a single point for each. The axes represent the absolute values of horizontal and vertical separation, respectively, at minimum slant range. Without using the BCAS resolution logic, and with no jitter, each of the scenarios should produce a point at the origin of the plot (0, 0). However, for each of the 20 repetitions, the simulation jitters the scenarios causing the results to be somewhat dispersed. In this way, many variations of a particular scenario are produced to test the effectiveness of the BCAS logic. When the BCAS resolution logic is applied to each jittered scenario, the desired effect is to move each scenario point away from the origin.

The simulation assumes that all straight flight trajectories have a constant speed and that all turns are established instantaneously. The true horizontal trajectories, therefore, consist of patched straight lines and constant radius circles. The numerous combinations of straight flight and turn maneuvers allows the user to generate a rich variety of encounter cases.

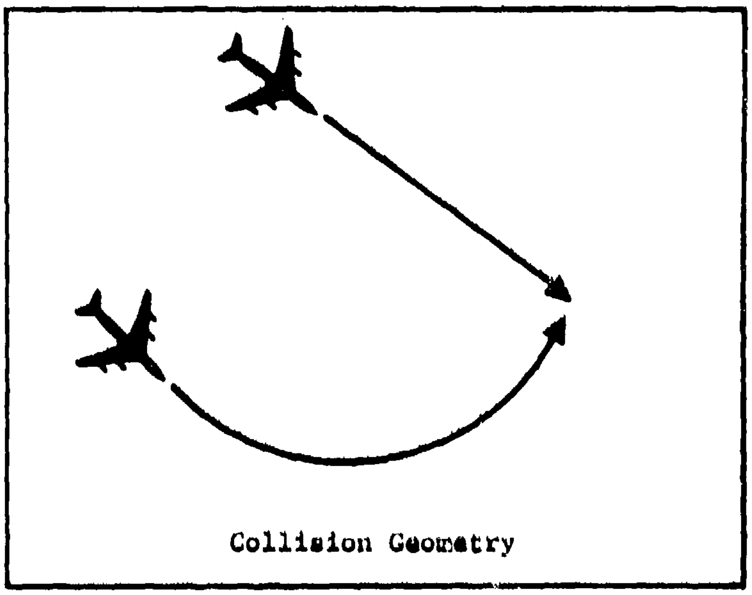
Figure 8-3 is an example of the vertical trajectory of a collision scenario. The vertical trajectories in this simulation program consist of segments of level flight, constant rate climb or descent and constant vertical acceleration.

8.2.1 Measurement Error Models

This program has error models for the BCAS surveillance system, the other aircraft's transponder, and the altimeters that generate noisy vertical position report data. Table 8-2 ennumerates the significant simulation parameters and the nominal value of each.

8.2.2 Transponder/Interrogator Error Models For Range Reports

The actual range report for an individual aircraft on a given BCAS logic cycle is generated by adding a bias and jitter error from the intruder's transponder, and a bias and jitter error from own BCAS' transponder to the true range between the



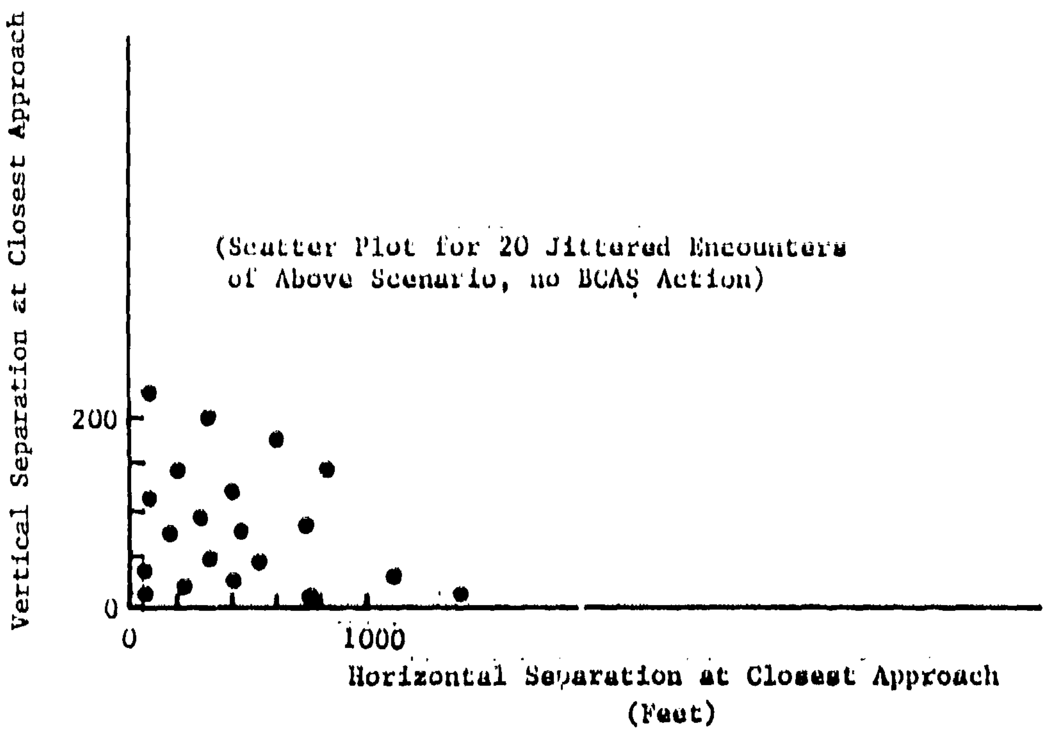


FIGURE 8-2
HORIZONTAL PLOT OF AN INPUT SCENARIO AND ITS RELATIONSHIP TO THE JITTERED ENCOUNTERS

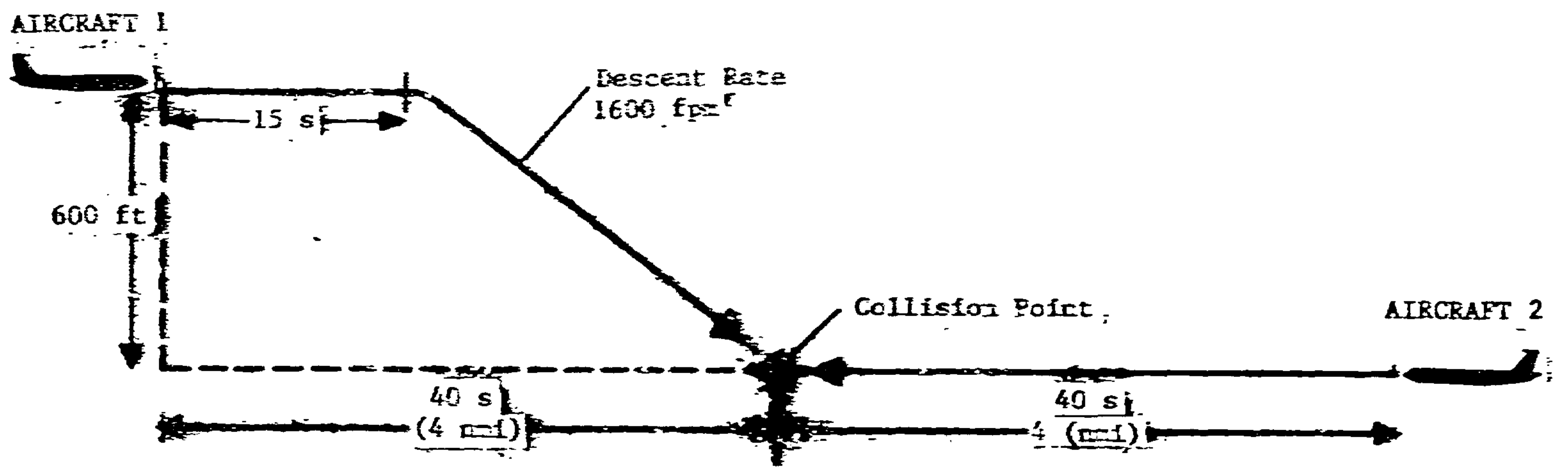


FIGURE 8-3
THE VERTICAL TRAJECTORY OF A COLLISION SCENARIO

TABLE 8-2

SIGNIFICANT MONTE CARLO SIMULATION PARAMETERS

Simulation Characteristics	Value
Number of Repetitions for Each Scenario	20
Data Update Rate	Once Per Second
Percent of Cycles With Successful Surveillance Reports	100%
Nominal Escape Climb Rate	1,000 fpm
Nominal Escape Descent Rate	-1,000 fpm
Nominal Acceleration Rate	1/3 g
Mean Value of Random Maneuver Delay*	5 seconds
1 Sigma of Deviation Applied to Escape Rates	100 fpm
1 Sigma of Deviation Applied To Acceleration Rate	1/30 g
Range of Deviation Applied to Maneuver Delay	± 2 seconds
1 Sigma of Aircraft Initial Position Jitter	420 ft
1 Sigma of Aircraft Initial Velocity Jitter	1%
1 Sigma of Aircraft Initial Altitude Jitter	60 ft
1 Sigma of Transponder Range Bias Error	120 ft
1 Sigma of Cycle-to-Cycle Jitter in Transponder Range Error	60 ft
1 Sigma of Altimetry Bias Error (Before Quantizing) for Equipped Aircraft	64 ft
1 Sigma of Altimetry Bias Error (Before Quantizing) for Unequipped Aircraft	100 ft
1 Sigma of Cycle-to-Cycle Jitter in Altimetry Error (Before Quantization)	6.4 ft

*Measured from Time of Advisory Display to Time the Aircraft's Path Begins to Change as a Result of the Advisory

aircraft. (The bias values remain constant during the encounter, but are different for each individual aircraft.) The jitter errors are generated anew on each logic cycle and are generated independently of previous values.

8.2.3 Mode C Error Models

The altimetry report errors are composed of a constant bias and a cycle-to-cycle jitter. In addition, 100 foot quantizing is simulated. The altimetry error values selected for this study appear in Reference 8. They are based on a significant study of raw flight test data gathered for general aviation aircraft and on published data for air carrier aircraft.

8.2.4 Pilot and Aircraft Response Models

In response to resolution alerts issued by the Beacon Collision Avoidance System, a pilot would direct the aircraft into a vertical escape maneuver. However, the actual response is subject to many factors such as the pilot's response time (delay), acceleration, and final escape rate. All of these effects have been modelled by specifying nominal response delay, acceleration, and escape rate and by specifying slight variations about these nominal response parameters.

The maneuver delay time used in this simulation study is less than the 7 second value used in past studies. The 5 second mean delay was selected as a result of the ARINC Research Corporation's real time cockpit simulator study. ARINC's findings concluded that the average response time was less than 4 seconds, (see Reference 14). However, alerts occurred frequently during the study, and subject pilots knew they would receive alerts. In the real world, alerts would be more unexpected and pilot delay might be longer. Therefore, five seconds was selected as a compromise.

8.3 Description of BCAS Logic Module

The Active BCAS logic and parameter values which are coded in the Monte Carlo Simulation Program are consistent with those found in a January 1980 draft BCAS Logic Document. This version of the logic was never published. It was, however, a version that was tested extensively during 1980. Results of operational flight testing of this logic are reported in Reference 11. This version of the logic represented a stage in the evolution of the BCAS logic from the version reported in Reference 7 to that reported in Reference 15. The parameter values used in this simulation analysis and in Reference 7 are the same as those

presented in Figure 3-11. As the simulation program 'moves' each aircraft one cycle at a time, the BCAS logic is invoked to determine whether or not an alert should be generated according to the performance level thresholds selected at the start of each run. When an alert is selected the simulation 'flies' the appropriate aircraft according to the alert selected and the aircraft/pilot models specified. All necessary information such as time history and minimum separation before and after resolutions are stored and available for output.

8.4 Monte Carlo Results

This section will present the results of each Monte Carlo run. The runs, unless otherwise stated, made use of the nominal BCAS parameter values recommended for each performance level region as shown in Figure 3-11. The results include two types of computer-generated output, scatter plots grouped by aircraft equipage and performance level regions, and individual encounter characteristic plots.

8.4.1 Protection When Both Aircraft Are Equipped (Error-Free)

A single repetition of the 15 midair scenarios was simulated in an 'error-free' environment using the performance level appropriate to each scenario. Both of the aircraft in every scenario were modelled to be equipped with BCAS. Although the St. Louis midair probably occurred in an area in which BCAS alerts would not have been displayed, it has been included in this first run, using performance level 3 parameters. In order to achieve an error-free environment, several simulation characteristics which are normally applied in the Monte Carlo mode were suppressed. Specifically, the jitter in each aircraft's initial position, velocity, and altitude was eliminated; the deviation in each aircraft's acceleration and escape rates, and deviation in the maneuver response delay was zeroed; and each aircraft's altimetry bias errors and jitter were zeroed. The result of eliminating these simulation characteristics for this run was to recreate each midair geometry as a single true collision geometry, prior to applying the BCAS detection and resolution logic. The logic can then be analyzed based on its performance in providing separation protection to the 15 individual collision geometries.

Figure 8-4 is a scatter plot showing the separation at closest approach of the 15 scenarios without the BCAS logic in effect. The closest approach point is as close to the origin (0, 0) as it could be made. Several of the data points are overlapped due to the small initial separations.

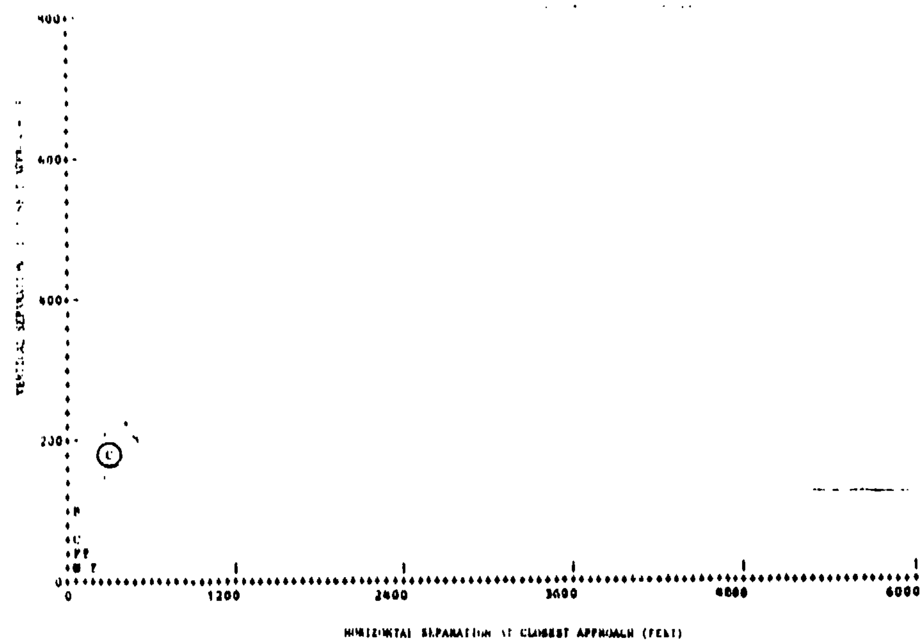


FIGURE 8-4
SEPARATION AT CLOSEST APPROACH WITHOUT BCAS RESOLUTION FOR ALL 15 MIDAIR SCENARIOS IN AN 'ERROR-FREE' ENVIRONMENT

Figure 8-5 shows the separation at closest approach for each scenario when the BCAS logic was applied. The data used for the scatter plots is derived from the true positions of the aircraft, rather than their tracked positions. Thus, the scatter plots indicate how much separation the aircraft truly had, not how much separation the BCAS logic thought they had on the basis of erroneous data. In this run, using an 'error-free' environment, the BCAS resolution logic provided in excess of 150 feet vertical separation at closest approach, without exception.

One anomaly does exist which should be pointed out. The third scenario in performance level 5, which occurred in Carmel, New York is circled on the scatter plots. The simulation which was run without applying the BCAS logic did not result in a collision course. Due to a combination of the sampling technique effects and the very high horizontal and vertical rates involved in this scenario, the vertical separation was about 170 feet, as seen in Figure 8-4. The separation which results when the BCAS logic is applied is about 150 feet, as seen in Figure 8-5. Therefore, BCAS resolution logic was not effective in providing separation protection for the Carmel scenario. This scenario is discussed in detail in Section 8.4.5.2.

Obviously, the BCAS logic will not be operating in an 'error-free' environment once it is put aboard commercial aircraft. However, it is useful to compare BCAS performance on the basis of the accuracy of its input data. When BCAS is given accurate data on intruder aircraft, its protection performance is excellent. The next four sections show the effects which simulated errors have on BCAS performance.

8.4.2 Protection When Both Aircraft Are Equipped (Impact of Errors)

Scatter plot Figures 8-6 through 8-8 represent the separations that would exist at closest approach for 20 repetitions of the scenarios in each performance level if the BCAS resolution logic were not applied. Figures 8-9 through 8-11 represent the minimum separation achieved for the 20 repetitions of each pair after simulating the BCAS logic. In each performance level, both aircraft in every scenario were modelled to be BCAS equipped and separation at closest approach was recorded.

Although each of the scenarios represents an actual midair collision geometry, the altitudes and ranges for each of the 20 repetitions were jittered according to input jitter models. The result of the jittering is to create the separation distributions seen in the first three plots. Each symbol on the

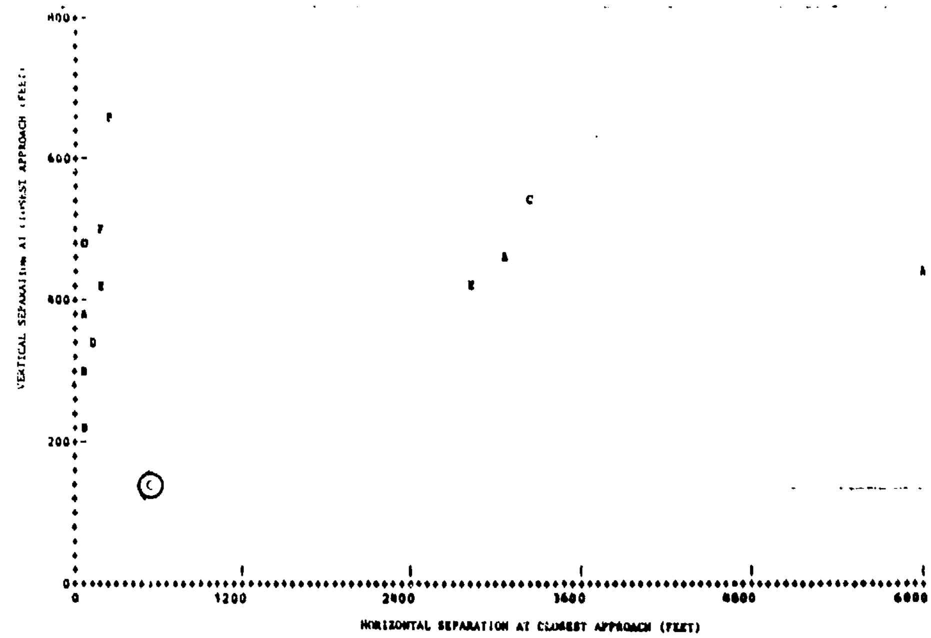


FIGURE 8-5
SEPARATION AT CLOSEST APPROACH WITH BOTH EQUIPPED FOR ALL 15 MIDAIR SCENARIOS IN AN 'ERROR-FREE' ENVIRONMENT

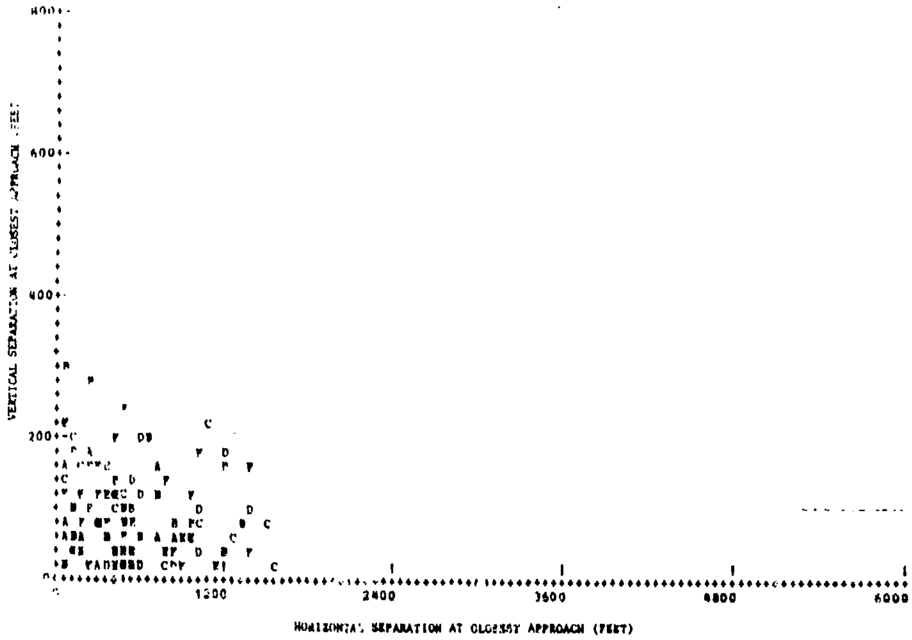


FIGURE 8-6
SEPARATION AT CLOSEST APPROACH WITHOUT BCAS RESOLUTION FOR PERFORMANCE LEVEL 3 MIDAIR SCENARIOS

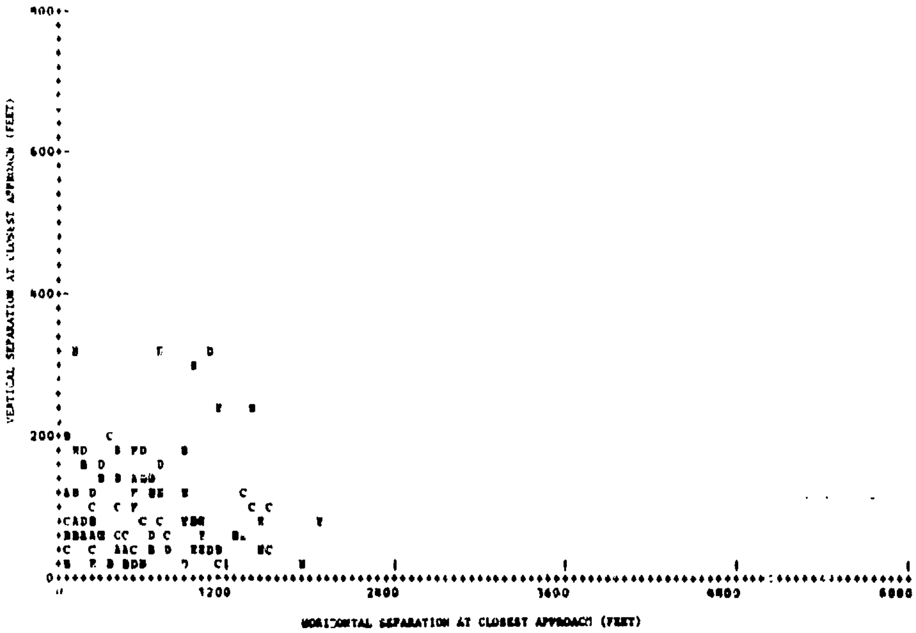


FIGURE 8-7
SEPARATION AT CLOSEST APPROACH WITHOUT BCAS RESOLUTION FOR PERFORMANCE LEVEL 4 MIDAIR SCENARIOS

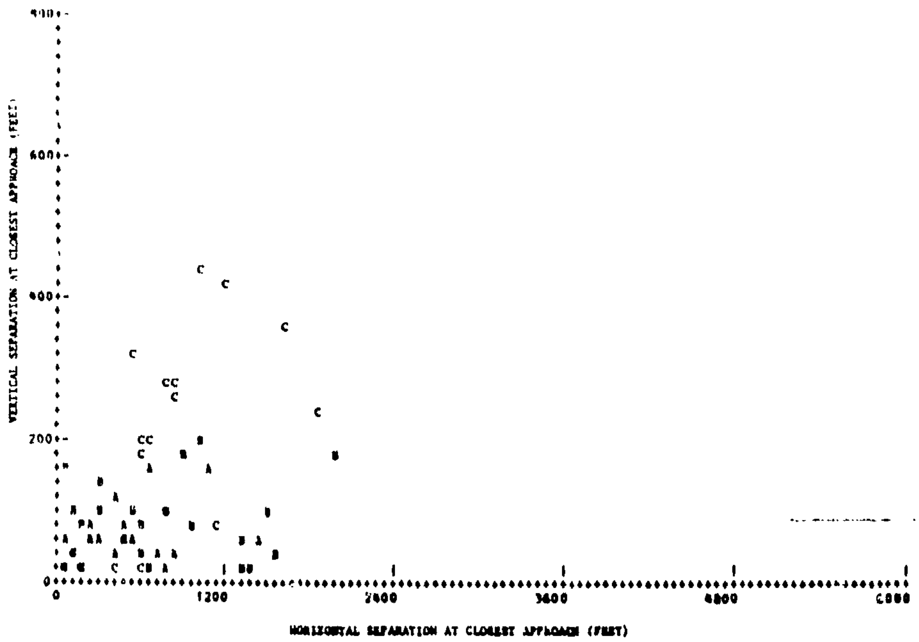


FIGURE 8-8
SEPARATION AT CLOSEST APPROACH WITHOUT BCAS RESOLUTION FOR PERFORMANCE LEVEL 5 MIDAIR SCENARIOS

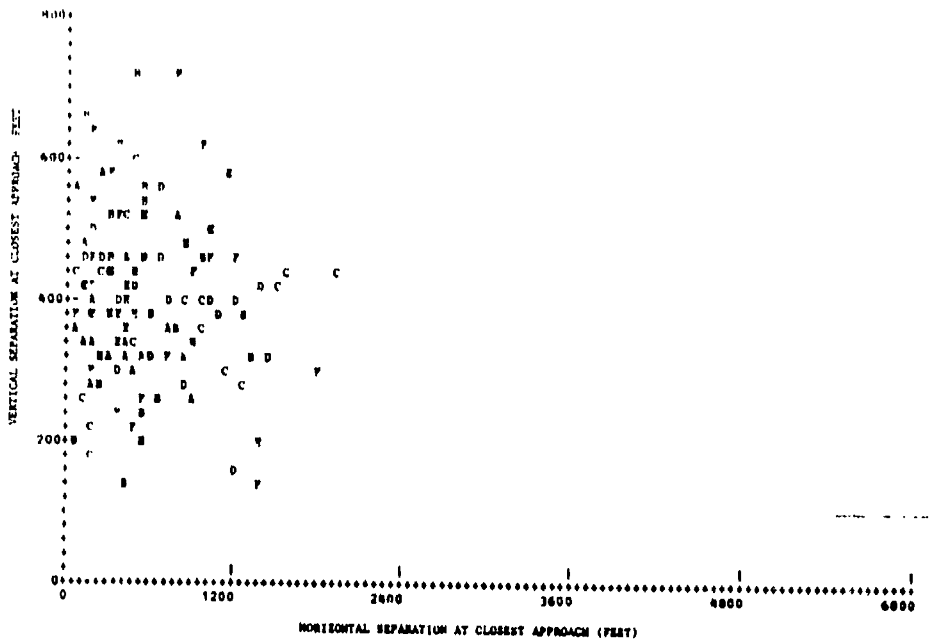


FIGURE 8-9
SEPARATION AT CLOSEST APPROACH WITH BOTH EQUIPPED FOR PERFORMANCE LEVEL 3 SCENARIOS

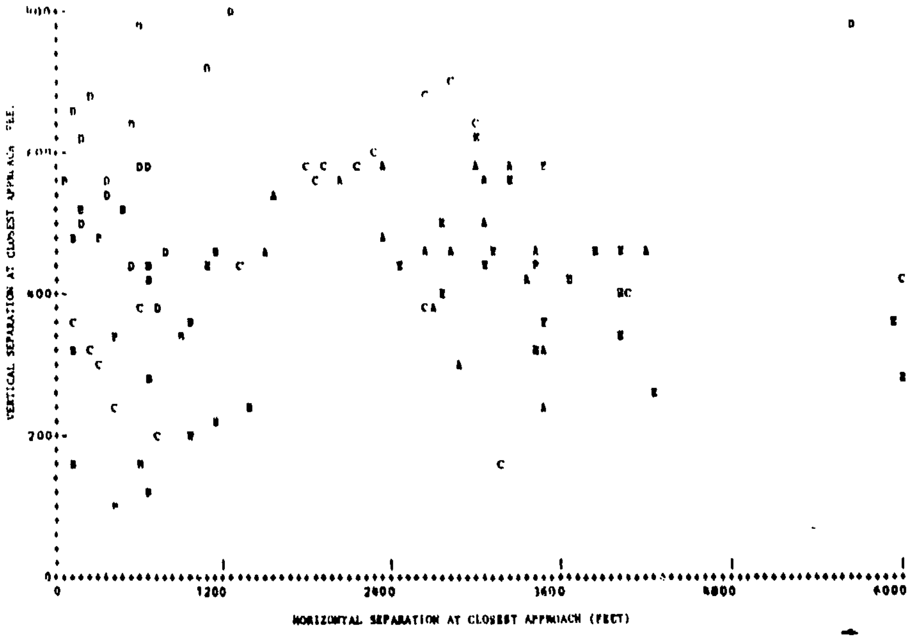


FIGURE 8-10
SEPARATION AT CLOSEST APPROACH WITH BOTH EQUIPPED FOR PERFORMANCE LEVEL 4 SCENARIOS

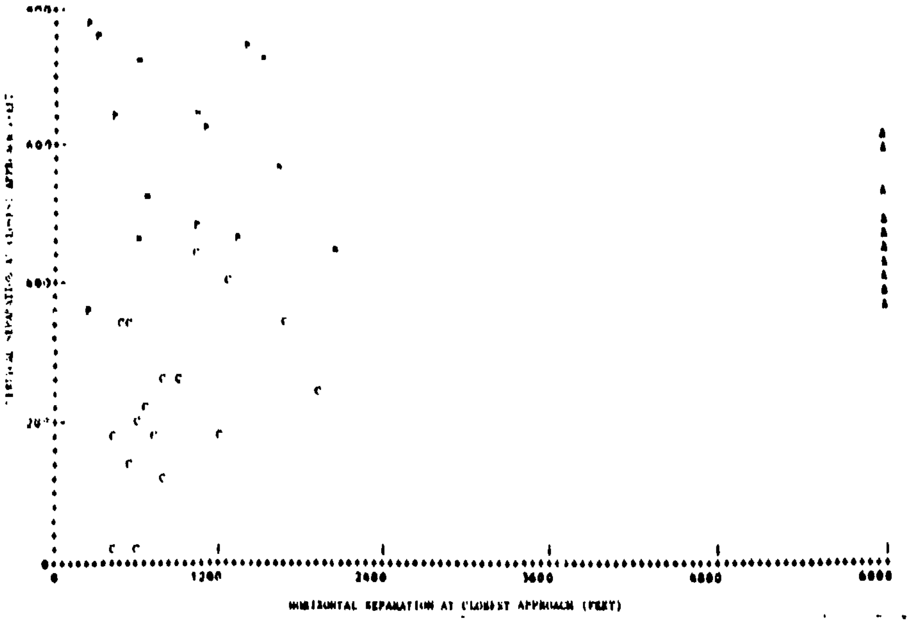


FIGURE 8-11
SEPARATION AT CLOSEST APPROACH WITH BOTH EQUIPPED FOR PERFORMANCE LEVEL 5 SCENARIOS

plots represents one encounter. The same symbol is used for each encounter that is derived from the same scenario. Since each scenario is jittered 20 times, 20 points will appear on a plot with the same character. Individual data points can be traced to their appropriate midair geometry by looking up the letter in Figure 8-1 in its corresponding performance level group. For example, letter 'B' in Figure 8-9 (performance level 3) is actually midair number 2 while 'B' in Figure 8-10 (performance level 4) corresponds to midair number 8.

The most important feature of the scatter plots is the ease with which separations can be compared before and after the BCAS logic is simulated. The effect of BCAS has obviously been to clear the mass of data points away from the origin of the plots. However, the results are not as good as those simulated in an 'error-free' environment. Error effects introduced into the simulation have caused slight degradation of the separation. The scenarios run in performance level 3 region achieved good separation with both aircraft responding to BCAS alerts (see Figure 8-9). For scenarios B and C, only one encounter in 20 failed to achieve vertical separation of 200 feet and horizontal separation of 1000 feet. This appears to be the tail end of the distribution of jittered simulation parameters. Encounters experiencing any combination of high altimetry errors, long response delay times and/or large tracker errors are expected to suffer from reduced separation.

In referring to some of the encounters which result in separations less than a certain threshold, the terms critical and failure will be adopted. A critical scenario is one which does not achieve a separation of at least 200 feet vertically or 1000 feet horizontally. A failure scenario is one which does not achieve separation of 100 feet vertically or 1000 feet horizontally.

Figure 8-10 also shows good separation resulting from a run of both equipped aircraft in performance level 4. However, scenario B of this group (Urbana, Ohio) shows some separation degradation by violating the critical area on the scatter plot. This scenario will be described in Section 8.4.5.

In the performance level 5 region shown in Figure 8-11, the effectiveness of the BCAS logic is shown to be very good except for scenario C (Carmel, New York). This scenario is the second midair for which BCAS does not always provide adequate protection. It will also be described in Section 8.4.5. While the results for scenario C seem to show that only two of the 20 encounters resulted in less than 100 feet vertical separation, this is misleading.

Actually, BCAS failed to provide any increase in separation for most of these encounters. This is evident by comparing the results without BCAS resolution (Figure 8-8) and the results with BCAS resolution (Figure 8-11). Because of the extreme vertical maneuver in the scenario, the effects of the jitter were to produce more variation than normal for this scenario, and many of the encounters had more than 200 feet separation without BCAS resolution.

Figure 8-12 is the scatter plot representing the three combined performance level runs. Due to the duplication of letters in each run, specific data points cannot be easily traced to their respective midair geometry. This plot is intended only to provide an overall view of BCAS separation protection in all performance regions.

8.4.3 Protection Against The Unequipped Intruder

As shown in the previous scatter plots, the BCAS logic almost always works effectively when both aircraft in an encounter are capable of responding to BCAS alerts, in spite of error effects. It is equally important to know what the BCAS protection is against the unequipped intruder. As was discussed in Section 5.2 of this report, a special logic exists which provides additional warning time against unequipped intruders with a vertical rate. This logic has been incorporated in the BCAS programs used by the Monte Carlo simulation. The threshold (ILEV) which determines whether or not an unequipped aircraft has a sufficient vertical rate to trigger this logic was set at 1,000 fpm.

Figures 8-13 through 8-15 are the scatter plot results of unequipped intruder runs grouped by performance level regions. Error effects have been simulated in these runs. Figure 8-16 represents the combined scatter plots. Compared to scatter plots of equipped runs, it is immediately evident that separation is reduced when only one aircraft can respond to BCAS alerts. Performance level 3, with its desensitized parameters, provides noticeably less separation because there is response by only one aircraft. Scenarios I, J, K and L have encounters falling in the failure area, below 100 feet vertical and 1,000 feet horizontal separation. Scenarios H, A, D and E have encounters which fall mostly in the critical area. Note that D and E are inverses of J and K, respectively (they are the same encounters with the equipage roles reversed). Investigation of the failure encounters shows that D and E share the same failure causes.

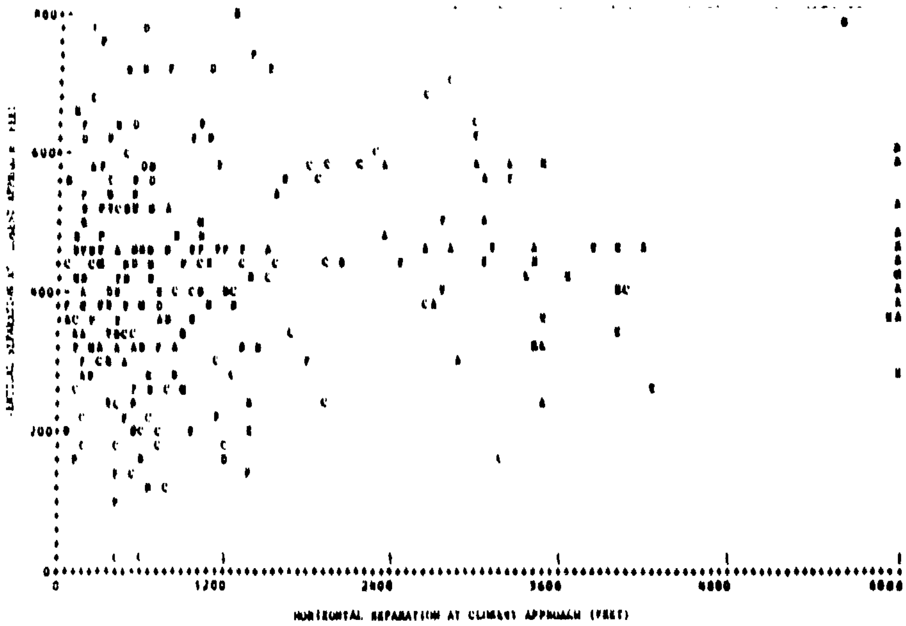


FIGURE 8-12
SEPARATION AT CLOSEST APPROACH WITH BOTH EQUIPPED: COMPOSITE OF PERFORMANCE LEVEL 3, 4, 5 SCENARIOS

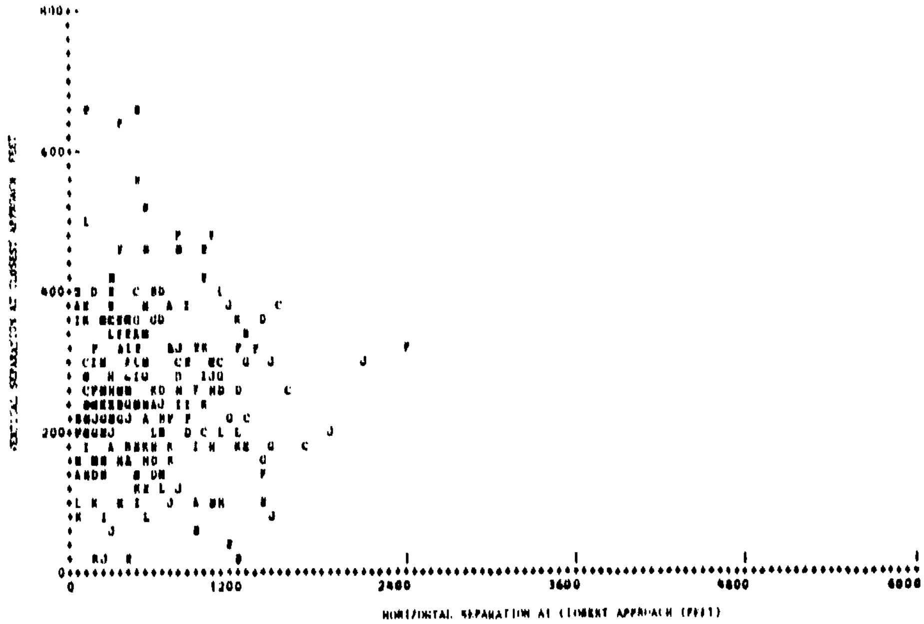


FIGURE 8-13
SEPARATION AT CLOSEST APPROACH WITH ONE UNEQUIPPED FOR PERFORMANCE LEVEL 3 SCENARIOS

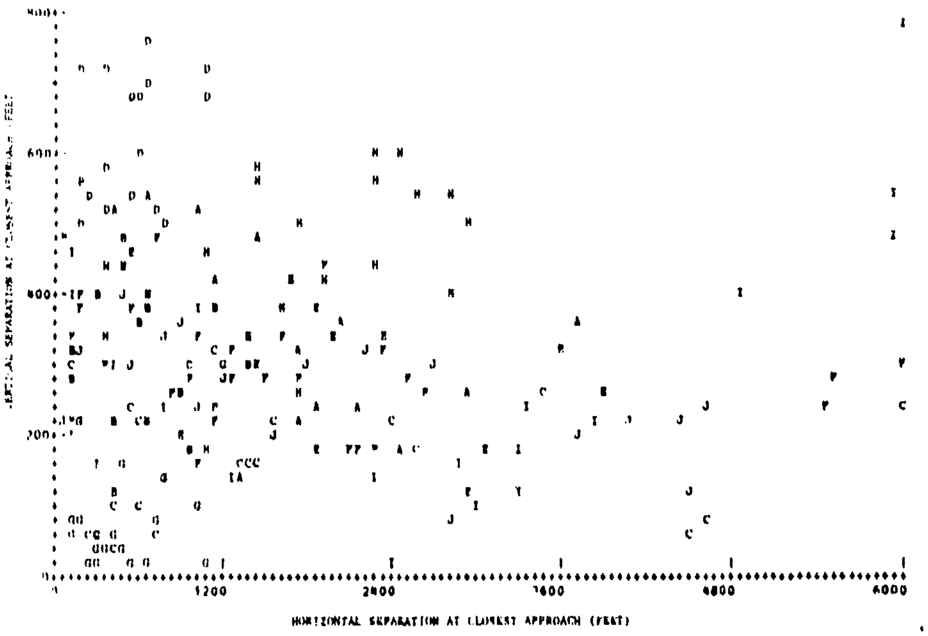


FIGURE 8-14
SEPARATION AT CLOSEST APPROACH WITH ONE UNEQUIPPED FOR PERFORMANCE LEVEL 4 SCENARIOS

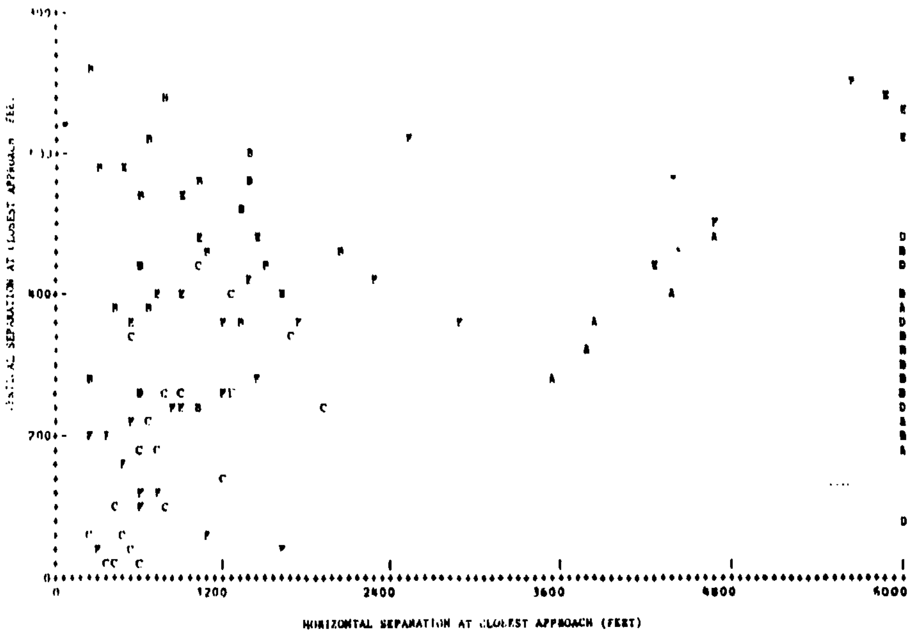


FIGURE 8-15
SEPARATION AT CLOSEST APPROACH WITH ONE UNEQUIPPED FOR PERFORMANCE LEVEL 5 SCENARIOS

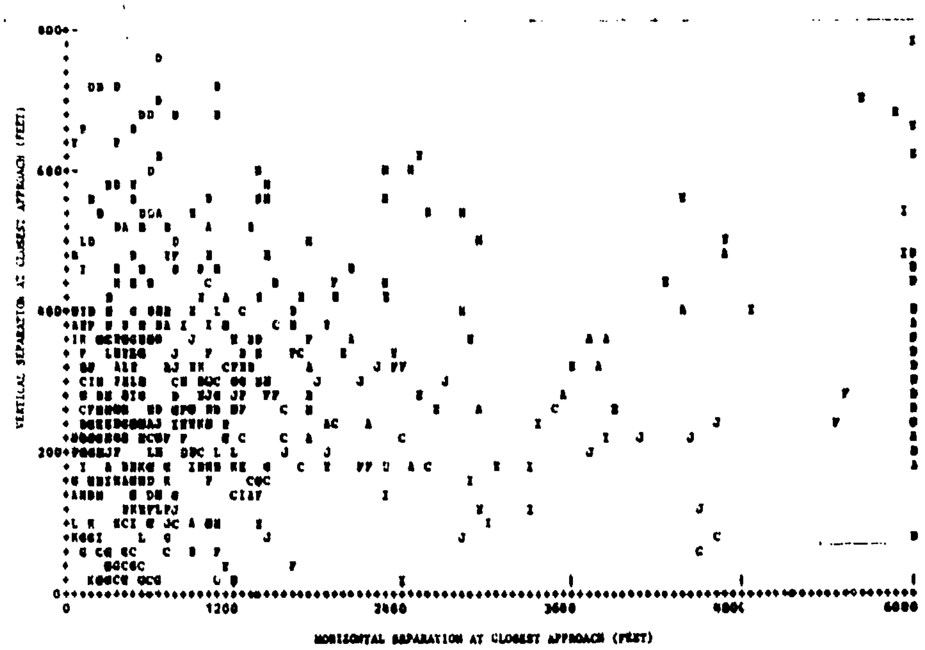


FIGURE 8-16
SEPARATION AT CLOSEST APPROACH WITH ONE UNEQUIPPED: COMPOSITE OF REGION 3, 4, 5 SCENARIOS

Performance level 4 had only 2 failure scenarios, G and C. Finally, the performance level 5 scatter plot shows that both scenario C and its inverse, F, have failure encounters.

It is very important to understand why the above scenarios failed. It is also important to determine which of the simulation error effects were significantly responsible for performance degradation.

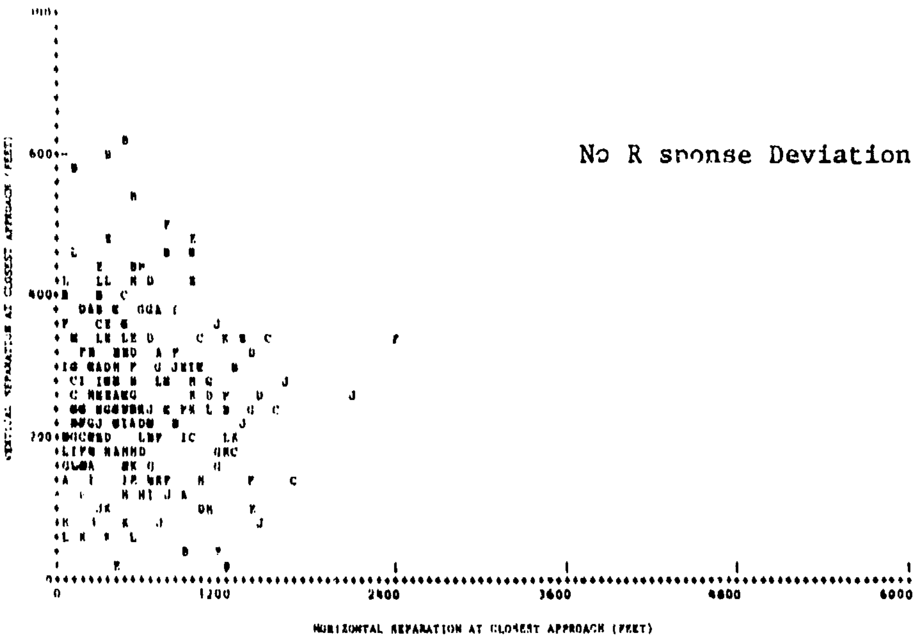
8.4.3.1 Comparative Analysis of Unequipped Intruder Logic Simulations

In order to isolate the various components which can lead to degradation of BCAS performance, three additional runs of the midair scenarios were made. The performance level 3 scenarios were chosen for this comparison, because these scenarios showed the greatest degradation in separation due to simulation variations. In each run, one simulation characteristic was altered, and its effect on separation analyzed. First, the standard deviations in acceleration, escape rate, and pilot response delay were zeroed. As a result, each repetition of the scenarios was modelled using deterministic input values of 1/3 g, 1,000 fpm, and 5 seconds, respectively with zero deviation. All other scenario characteristics were left unaltered.

Figure 8-17 shows the result of the run with zero deviation appearing above the nominal run of the same scenarios. The difference in the scatter plots is so small as to be insignificant. It is therefore concluded that the standard deviation of 10 percent in the acceleration and escape rates and the 2 second standard deviation in pilot response delay alone do not noticeably degrade BCAS logic performance.

The next simulation characteristic which was altered was the vertical tracking algorithm. In order to assess the impact of tracker lag on separation performance, the simulation logic was altered to provide true rather than tracked altitude rates to the BCAS detection and resolution algorithms. Standard deviations were set to their nominal values. All other simulation characteristics remained unchanged at their nominal values.

Figure 8-18 shows the result of the run with the true vertical tracking input appearing above the nominal run, using the standard alpha beta tracking algorithm. As in the previous run, this comparative run shows little difference in separation



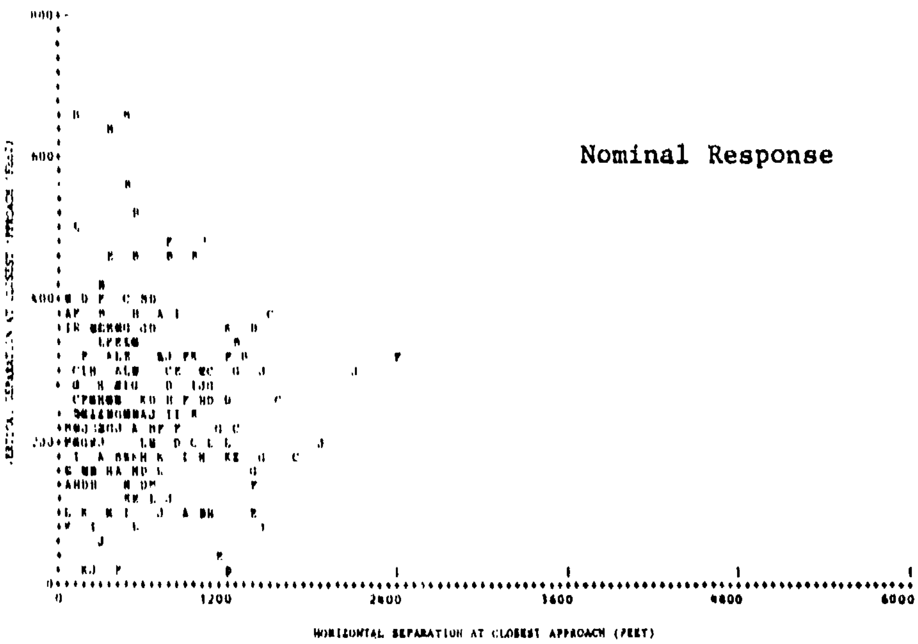
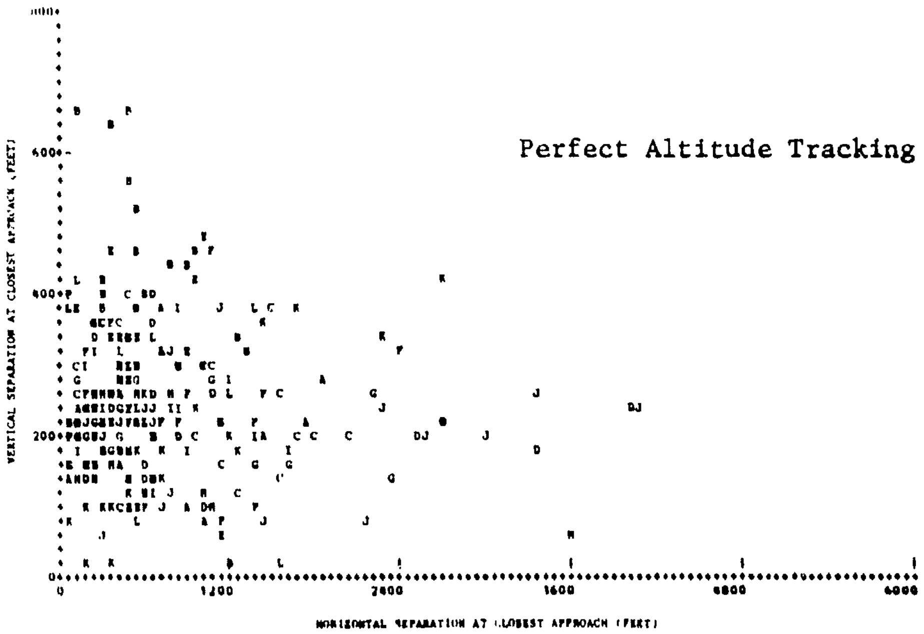


FIGURE 8-17
COMPARISON PLOTS OF NOMINAL RESPONSE VERSUS NO RESPONSE DEVIATION (PERFORMANCE LEVEL 3 SCENARIOS—ONE UNEQUIPPED)



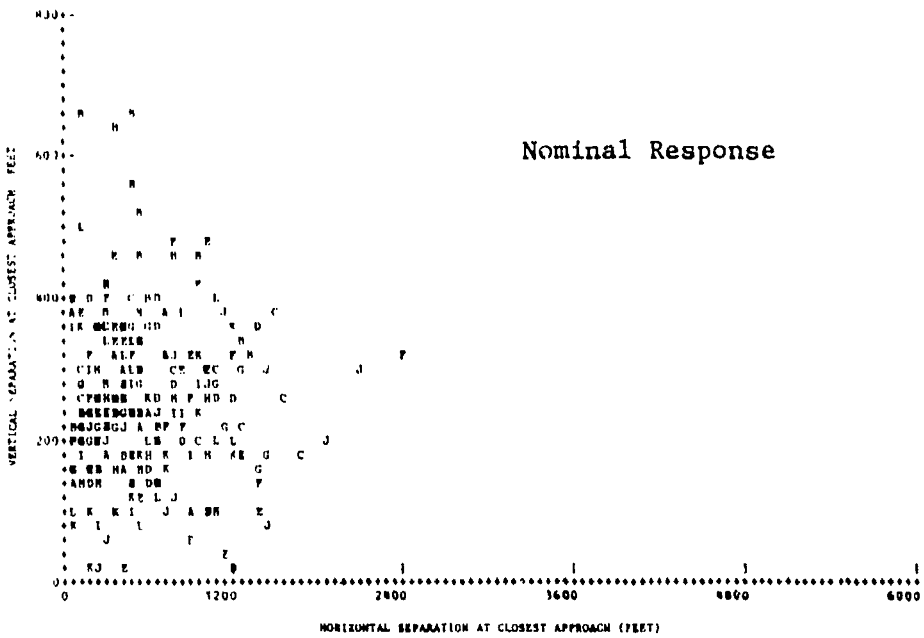


FIGURE 8-18
COMPARISON PLOTS OF NOMINAL RESPONSE VERSUS PERFECT ALTITUDE TRACKING (PERFORMANCE LEVEL 3 SCENARIOS—ONE UNEQUIPPED)

protection. The midair collisions which occurred in close proximity to the airports consisted mostly of gradual and sustained vertical maneuvers rather than sudden high vertical rate maneuvers. Therefore, the alpha beta tracking algorithm provided sufficient accuracy for conflict detection and resolution of these scenarios.

The final characteristic which was altered was the altimetry error input. The Mode C bias was zeroed, along with the cycle-by-cycle altimetry jitter. All other simulation characteristics remained unchanged at their nominal values. In the top plot of Figure 8-19, the improvement in separation is immediately evident when zero altimetry errors are simulated. No encounters resulted in less than 100 feet vertical separation. The nominal run appears on the bottom.

Altimetry errors can impact collision avoidance logic by causing unnecessary alerts, by causing late or missed detection of conflicts, or by causing selection of an altitude crossing advisory. An altitude crossing avoidance maneuver can be characterized as follows: BCAS instructs the pilot of an aircraft which appears to be at a higher altitude to climb, but due to errors, the aircraft is actually at a lower altitude and is therefore instructed to climb through the altitude of the other aircraft. The altitude crossing effect of altimetry errors is the most serious because it cannot be corrected simply by making logic parameter changes. While varying the value of the ALIM threshold changes the tradeoff between missed detections and unnecessary alerts, it has no effect on the altitude crossing maneuver effects. In fact, there are no modifications that could be made to the BCAS logic or parameters that could prevent the BCAS from generating altitude crossing maneuvers. Only increasing the warning times to provide more escape time can help to overcome the effects of altimetry errors. Ideally, the warning time should be sufficient to permit an aircraft to maneuver through a distance composed of altitude error plus a safety buffer. The next section provides a detailed look at the effect which altimetry errors had on individual failure scenarios appearing in the nominal run.

8.4.3.2 Impact of Altimetry Errors

As shown in the preceding section the major cause of failure in the nominal runs is that the logic, with the escape rates simulated here, is not always able to overcome large altimetry errors. This is evident particularly in the performance level 3 region, where parameters are desensitized the most.

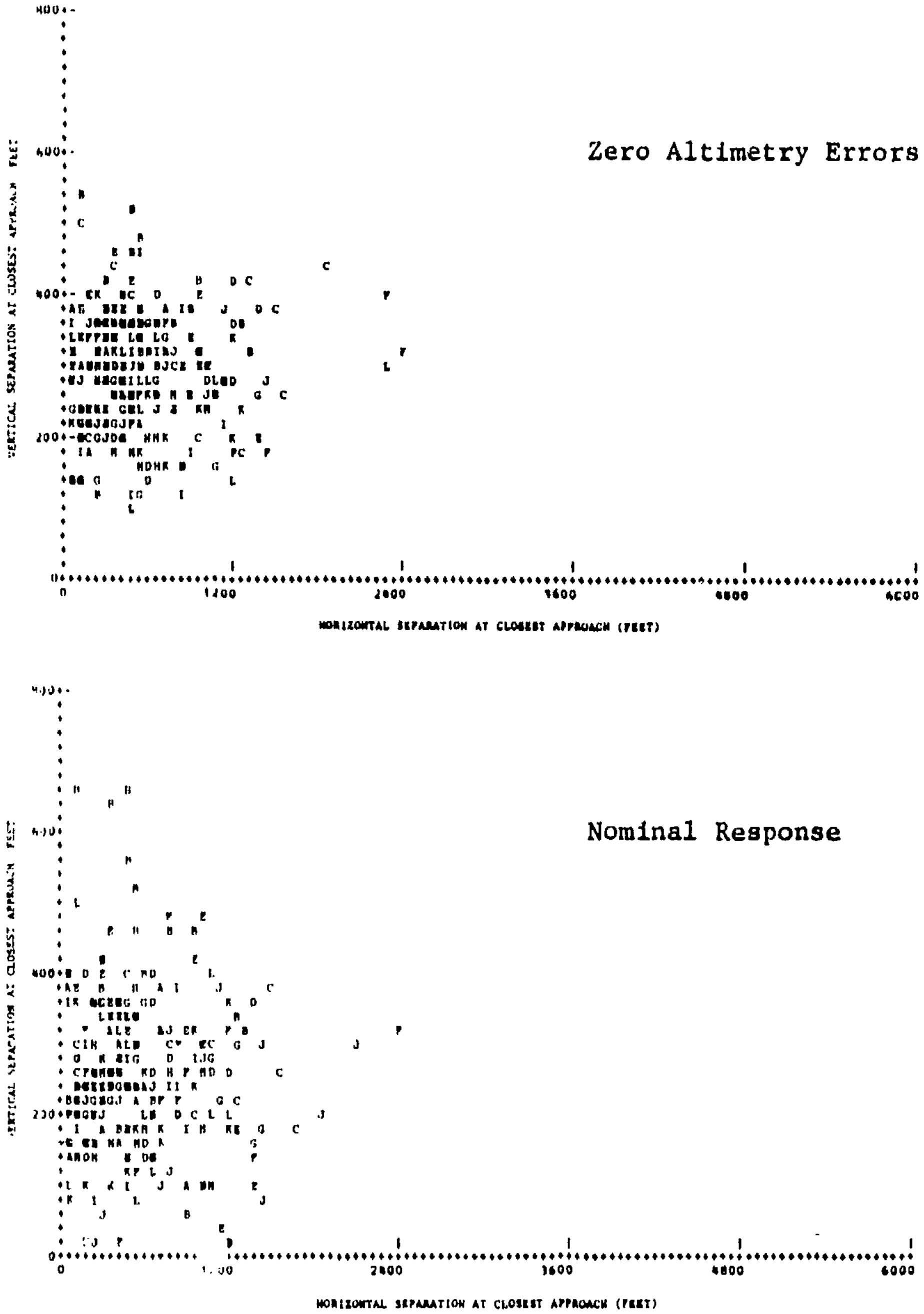


FIGURE 8-19
COMPARISON PLOTS OF NOMINAL RESPONSE VERSUS ZERO ALTIMETRY ERRORS (PERFORMANCE LEVEL 3 SCENARIOS— ONE UNEQUIPPED)

For many encounters the altimetry errors result not only in inaccurate data, but in data which is misleading to the BCAS resolution logic. Both J and A are non-accelerating performance level 3 scenarios which suffer from ineffective sense selection due to large altimetry errors. Figure 8-20 is a typical example of such a failure encounter for scenario J. The plot shows the tracked encounter characteristics of the scenario plotted against time. Above the uppermost plot, a command line appears which represents all BCAS alerts as they are displayed to the BCAS aircraft. Table 8-3 explains the symbology used in the command line.

The top of the three stacked plots in Figure 8-20 shows the tracked altitude of the BCAS aircraft (ZOWN) and the unequipped intruder (ZINT) along with the tracked range (R) plotted against simulation time (TCUR). The scale on the right corresponds to range in nautical miles. The middle plot shows the calculation in feet of current vertical separation (A) and projected vertical separation (VMD) also plotted against time. The two dotted lines extending horizontally through the plot represent the value in feet of the ZTHR and ALIM thresholds, respectively.

The bottom plot shows the behavior of the horizontal (TAUR) and vertical (TAUV) time to closest approach thresholds plotted against time. TAUV is plotted only when the range criterion has been met and the current altitude separation is greater than ZTHR. The dotted line represents the value of TRTHR and TVTHR corresponding to the particular performance level of each scenario.

To read this plot, it is easiest to look at the major criteria which lead up to selecting a command. First, the range criteria must be satisfied, i.e., TAUR must be less than 20 seconds. The bottom plot shows this occurring at time 56. The vertical threshold is then tested. When A falls below ZTHR, the detection logic criteria is satisfied and an alert is needed. The bottom plot shows this also to be true at time 56. The logic is then ready for sense selection. First, separation predictions are calculated for both climb and descend maneuvers by the BCAS aircraft. For these calculations, the tracked vertical rate of the intruder at the time of the calculation is used to linearly extrapolate the intruder's vertical position. In this scenario, the intruder is tracked to be level, therefore, no vertical maneuver is modelled for the intruder. The logic then assesses the vertical separation which would occur for each maneuver by the BCAS aircraft and selects the one which offers greatest separation.

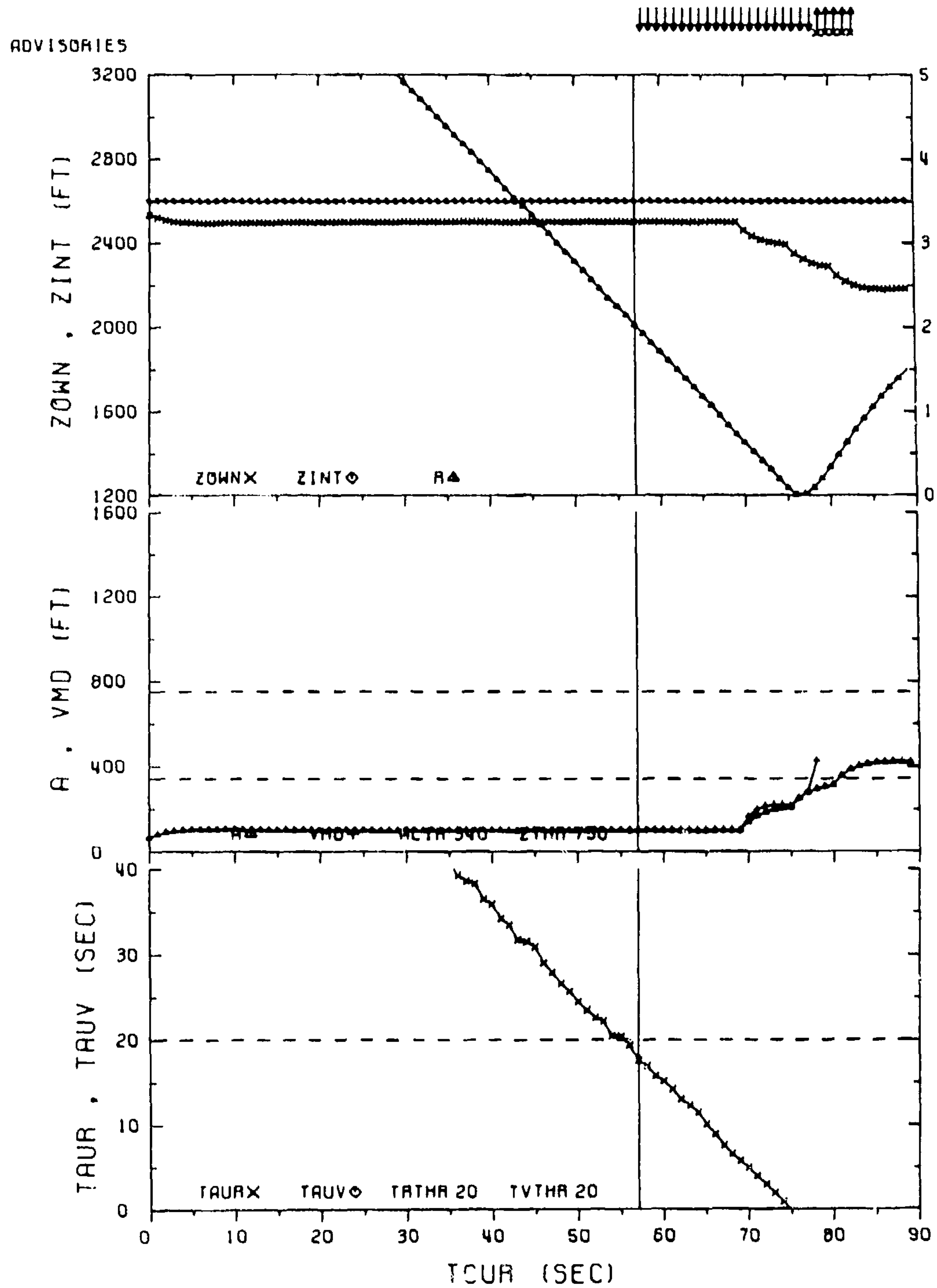


FIGURE 8-20
SEPARATION, TAU PLOTS FOR SCENARIO J IN PERFORMANCE LEVEL 3 (AN UNSUCCESSFUL RESOLUTION)

TABLE 8-3

COMMAND SYMBOLOGY

Symbol	Command
$\downarrow$	Descend
$\uparrow$	Climb
$\not\downarrow$	Don't Descend
$\not\uparrow$	Don't Climb

According to the tracked information, the BCAS aircraft is below the intruder by 100 feet at the time of alert selection. Actually, the true altitude shows the BCAS aircraft to be above the intruder by more than 110 feet. On the basis of the altitude data available to the BCAS logic, a DESCEND is selected for the BCAS aircraft. Once the alert sense is selected, the logic must determine the type of alert needed, positive, negative or VSL. A positive command is selected against a level unequipped intruder because the current altitude separation is below ALIM. The command line above the plot shows a DESCEND appearing at time 58. After a delay of 10 seconds, the BCAS aircraft can be seen to respond to the DESCEND at time 68 (refer to top plot).

Although tracked altitudes shown in the top plot appear to result in adequate vertical separation at closest approach, accompanying printed output which traces true altitude shows separation at closest approach to be only 59 feet vertically and 326 feet horizontally. Selecting a DESCEND for the BCAS aircraft proved to be ineffective. Assuming an escape rate of 1,000 fpm, an altitude error of 210 feet in the direction opposite the alert sense causes the aircraft pair to be converging in altitude for 13 seconds before they cross altitudes and actual vertical separation begins. A TRTHR value of 20 seconds does not provide sufficient time to compensate for this error.

Figure 8-21 represents one of the successful resolutions of scenario J. The altitude errors are much smaller in this case and are in the same direction as the true aircraft positions. The equipped aircraft is tracked at 100 feet above the intruder. Its true position is 70 feet above. A climb advisory for the equipped aircraft results in separation greater than 800 feet horizontally and 300 feet vertically. An important factor in this encounter is that, unlike the situation with the failure encounter, no altitude crossover resulted from following the BCAS advisory.

Scenario D in performance level 3 is the inverse condition of scenario J. Although D fails less often, the same error characteristics as those found in J can be found in its failure encounters.

Scenario H in performance level 3 is another example which shows the effects of altimetry errors. However, rather than causing an altitude crossing, the error causes a late alert to be issued. According to Figure 8-22, TAUR falls below TRTHR at

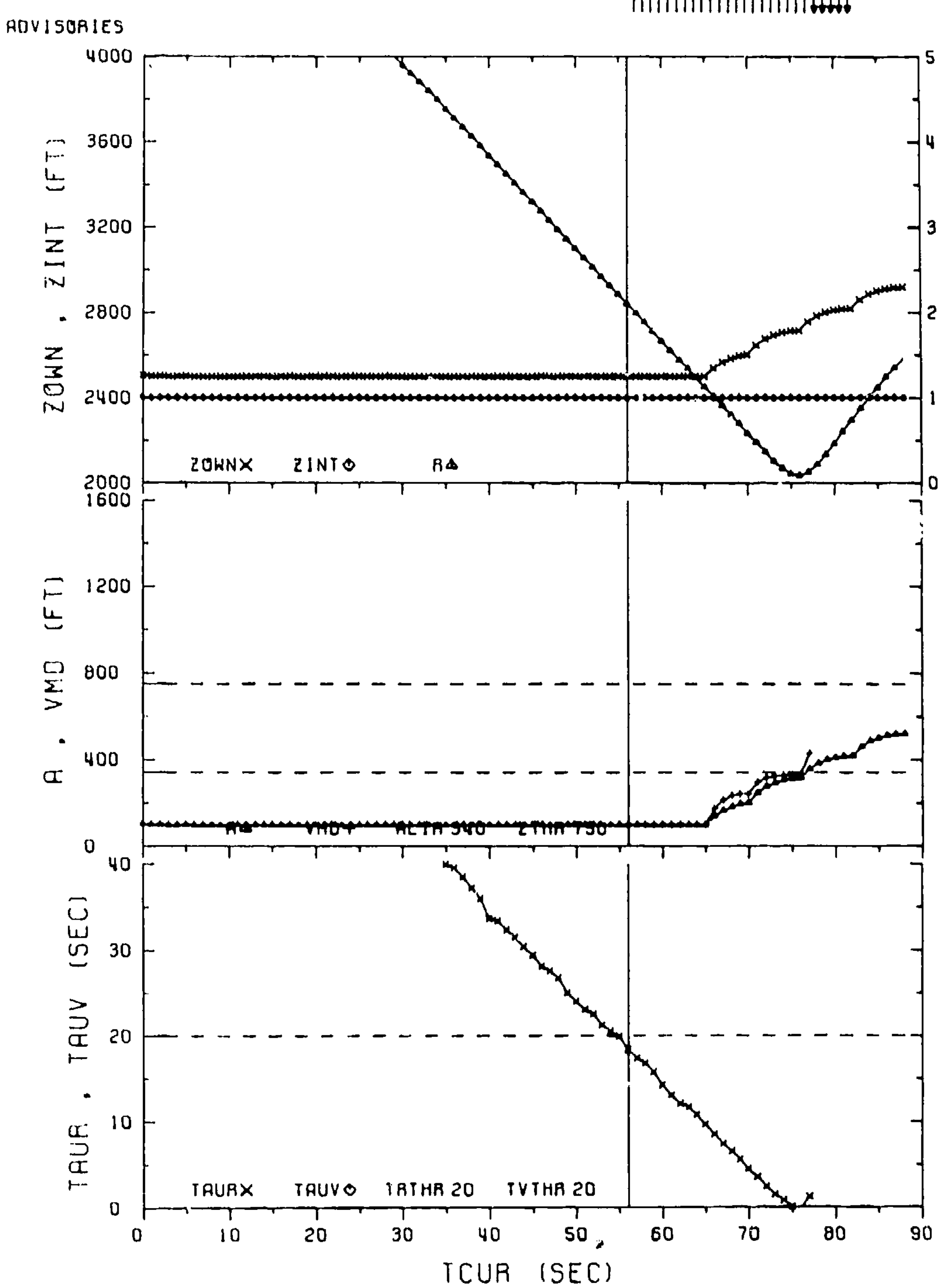


FIGURE 8-21
SEPARATION, TAU PLOTS FOR SCENARIO J IN PERFORMANCE LEVEL 3 (A SUCCESSFUL RESOLUTION)

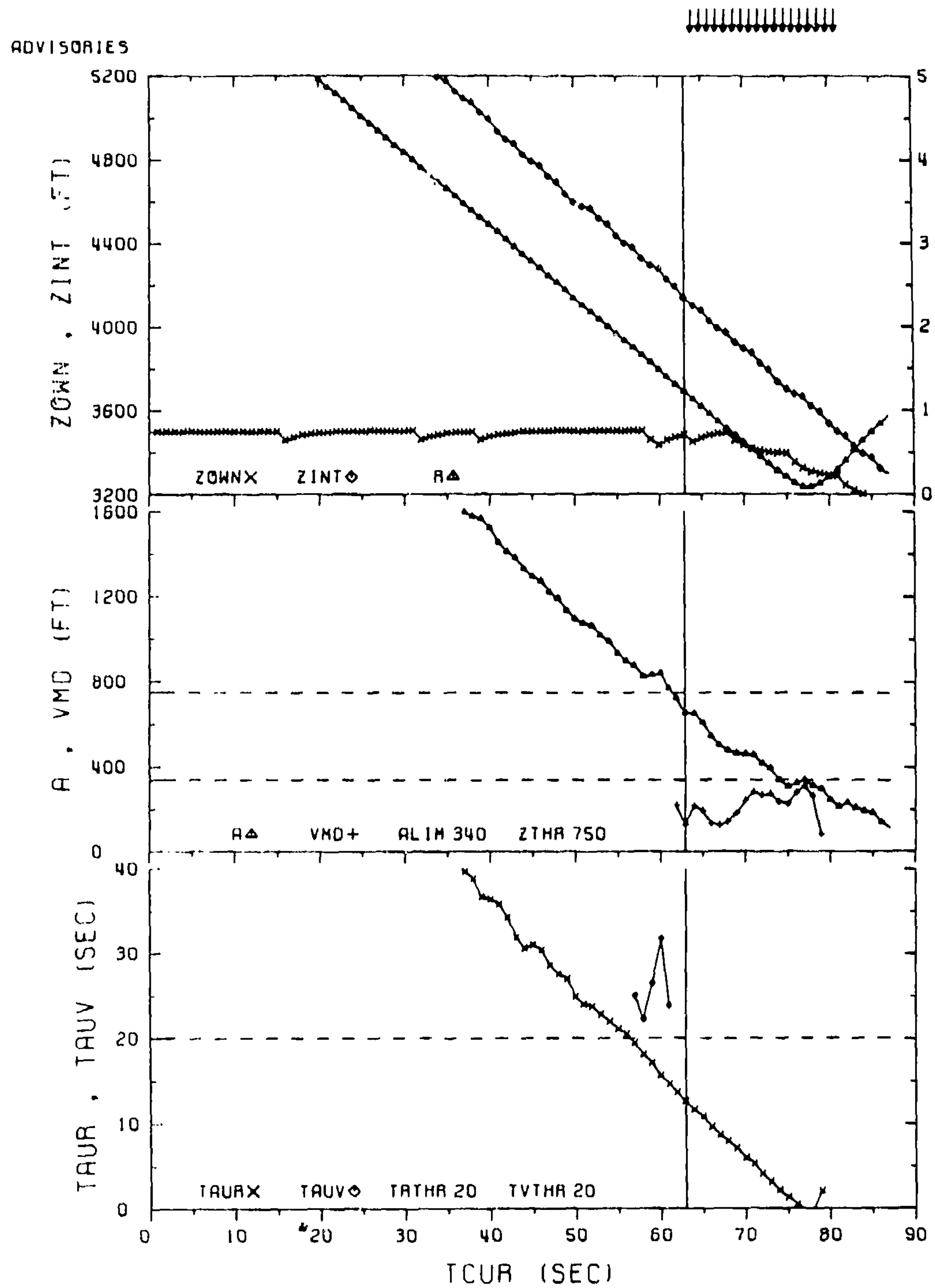


FIGURE 8-22
SEPARATION, TAU PLOTS FOR SCENARIO H IN PERFORMANCE LEVEL 3 (AN UNSUCCESSFUL RESOLUTION)

time 58. The altitude difference (A) between the pair at time 58 is tracked to be 876 feet. However, true A is only 703 feet, well below the ZTHR value. Had accurate altitude data been available, an alert could have been issued as much as 6 seconds earlier than shown in the alert line above the top plot (at time 64). The recorded vertical closest approach for this encounter was 144 feet. With the intruder descending at a rate of 2160 fpm, 6 seconds of extra escape time could have benefitted the BCAS aircraft by as much as 100 feet with a simulated escape rate of only 1,000 fpm.

Scenarios I, K, and L each have encounters which result in separations in the failure area. Altimetry errors are responsible, at least in part, for many of these poor results. Even when altimetry errors are not large enough in themselves to cause failures due to altitude crossing maneuvers, when combined with other factors such as vertical rate tracker lag, or long response delays, ineffective sense selection can result. However, altimetry error effects can be successfully overcome in the majority of encounters by increased pilot and aircraft response. Section 8.6 will discuss the results of higher escape rate simulations.

8.4.3.3 The ILEV Parameter

There has been a great deal of study involved in selecting optimum values for such parameters as TRTHR, DMOD, ALIM and ZTHR. One less critical parameter has been singled out in this analysis as having a direct effect on at least two scenarios. That parameter is ILEV, the threshold at which an unequipped intruder is considered to have a sufficient rate to warrant additional warning time. This study used a 1,000 fpm value, which is a very conservative threshold. The main criterion which must be satisfied in selecting ILEV is that a normal altitude step of 100 feet in either direction must not cause the unequipped intruder logic to be triggered. This is so because a 100 foot change could be observed due to the 100 foot quantization when the intruder really has no significant vertical rate. It is feasible to drop the ILEV value to 800 fpm in order to provide additional unequipped scenarios with extra warning.

A specific example benefitting from a smaller ILEV value is scenario C in performance level 4. The unequipped intruder is climbing toward the BCAS aircraft at 810 fpm. In the failure encounter, a DON'T DESCEND is given at time 32, when the intruder is tracked to be 491 feet below the BCAS aircraft. At

this time, true separation is only 303 feet. A positive CLIMB is finally displayed 13 seconds later at time 45, when the tracked altitude separation falls below 340 feet. When the delay time is factored in, 1,000 fpm response by the BCAS aircraft only results in 727 ft horizontal and 68 ft vertical separation. The same encounter was then rerun.

In contrast, when the ILEV parameter was lowered to 800 fpm as in Figure 8-23, projected altitude of the intruder triggered the unequipped logic at time 36, providing a positive CLIMB to the BCAS aircraft. This encounter was able to achieve 2,102 ft separation in range and 215 ft separation in altitude.

It is therefore recommended that the ILEV value be lowered to at least 800 fpm. It is possible that the new non-linear tracker could improve tracking response so that the value could be reduced even further. However, further testing should be conducted before recommending a value lower than 800 fpm.

8.4.4 St. Louis Midair Collision Simulation

A separate run was made of the St. Louis midair using the nominal simulation characteristics and assuming that one aircraft in each encounter was equipped with BCAS. Results are shown in Figure 8-24. With the few exceptions, each of the jittered encounters were able to achieve in excess of 100 feet vertical separation at closest approach. Those which did not were examined in detail. Three encounters of scenario 'B' failed to achieve 100 foot separation. Scenario B simulates the higher performance intruder aircraft with a 1050 fpm vertical rate as unequipped. Analysis of these failures clearly showed that, due to vertical tracker fluctuations, the unequipped intruder's rate sporadically fell below 1,000 fpm, the threshold (ILEV) at which an intruder is considered to have a sufficient rate to trigger the extra warning logic. As a result, these failure encounters either began with the issuance of a negative alert instead of a needed positive alert, or transitioned from a positive to a negative during a critical time in the conflict. Due to the advisory timer logic, the negative alert could not be updated to a positive for at least 5 seconds after it is first displayed, thereby compounding the ineffectiveness of the separation provided. Decreasing the ILEV value to 800 fpm should improve the separation for these encounters.

Although most of the 'A' encounters showed good separations on the scatter plot, two of the 'A' encounters (in which the aircraft with the vertical rate was simulated to be BCAS equipped) provided just barely 100 feet separation. Analysis of these encounters showed that the turning geometry of this

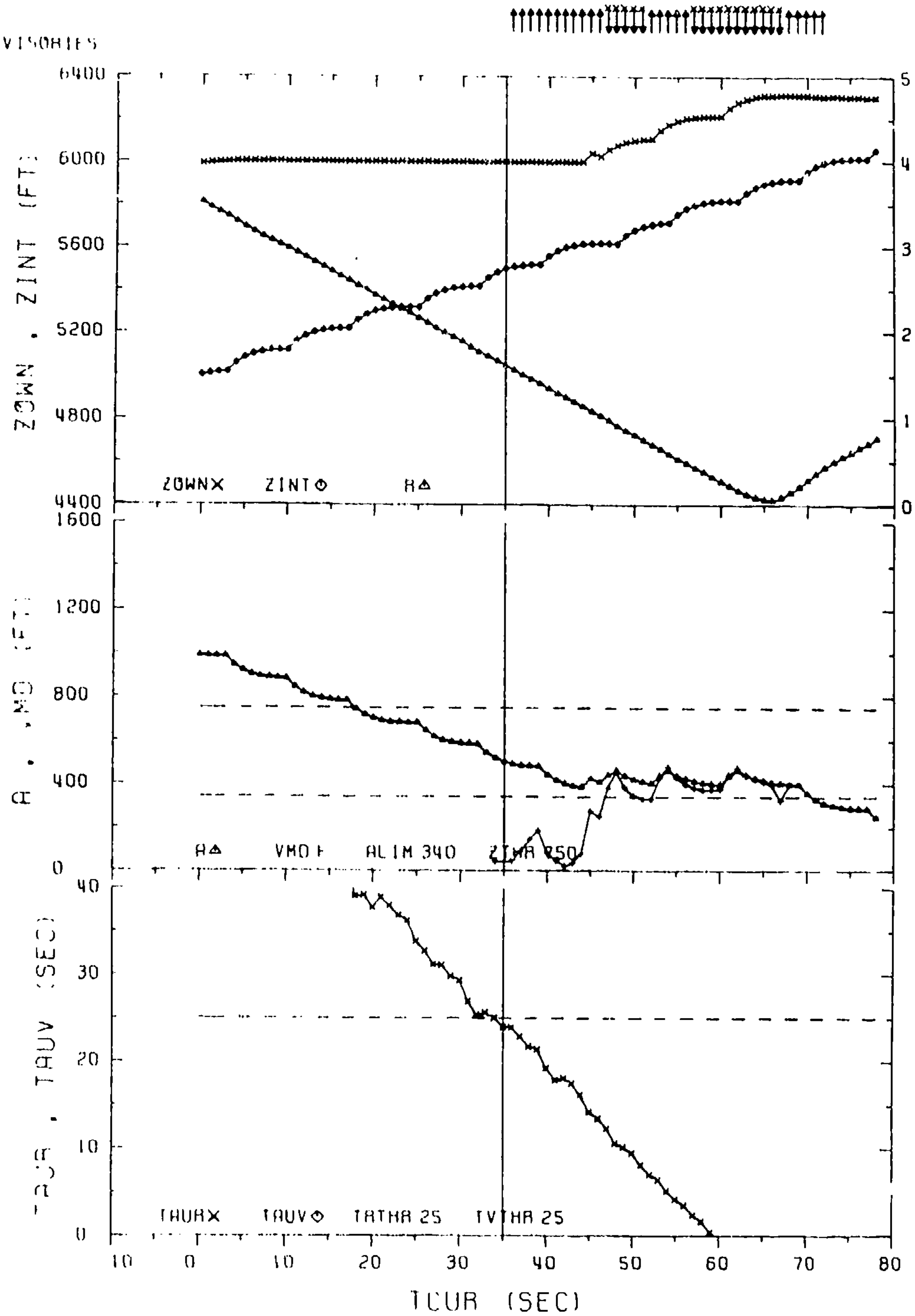


FIGURE 8-23
SEPARATION, TAU PLOTS FOR SCENARIO C IN PERFORMANCE LEVEL 4 (A SUCCESSFUL RESOLUTION)

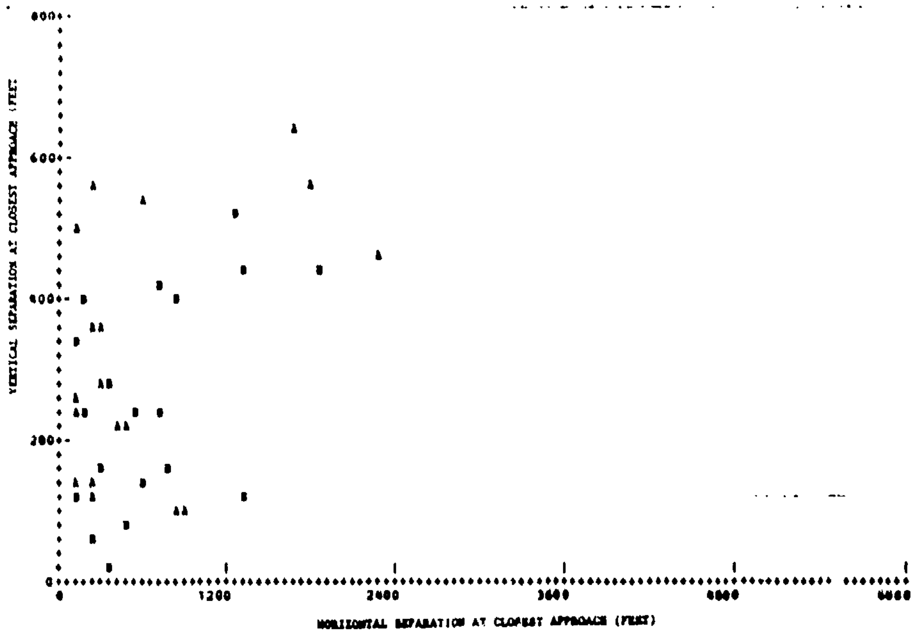


FIGURE 8-24
SEPARATION AT CLOSEST APPROACH WITH ONE UNEQUIPPED FOR ST. LOUIS SCENARIO

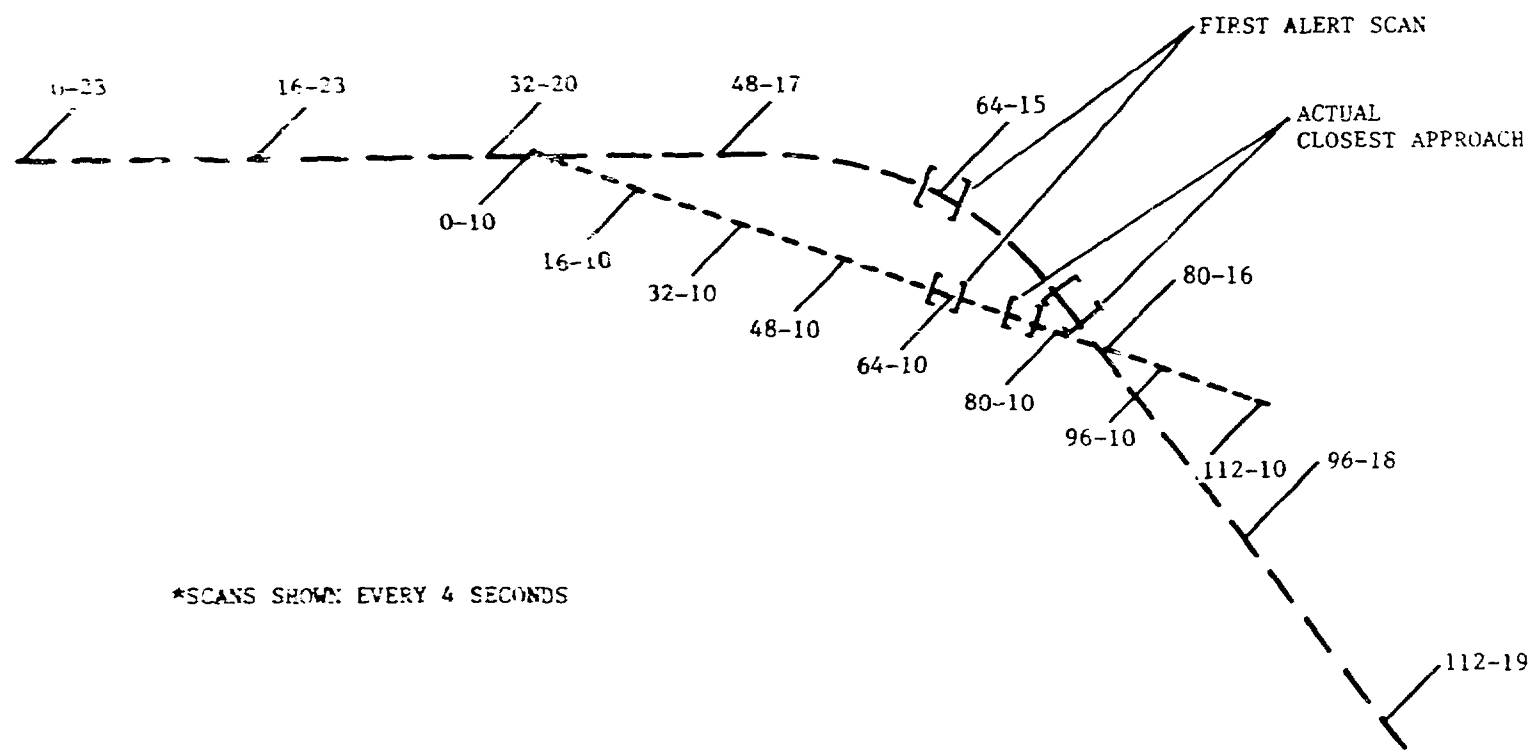
encounter causes inaccurate range tracking, which can lead to decreased warning time. The computed time to closest approach (modified TAUR) can differ significantly from true time to closest approach in turning scenarios. The computed closest approach time is also subject to sudden, rather large variations due to slight oscillations in tracked range rate. Figure 8-25 illustrates the inaccuracy of modified TAUR due to range tracking limitations. At scan 63, the scan immediately before a range threat is detected, modified TAUR predicts 20 seconds until closest approach using the tracked range values. The very next scan, scan 64, shows a drop in TAUR to 13 seconds and a 'hit' is declared. The time to closest approach computed using the true, rather than tracked range is 14 seconds at scan 63 rather than 20 seconds. Actual closest approach occurs within 12 seconds at scan 76. With a turning geometry, the protection tradeoff becomes much more significant with respect to reducing the value of DMOD. As the turning acceleration continues, the lag in range tracking also continues. A larger DMOD value would offset this effect by allowing the turning aircraft to be declared a threat earlier. However, in spite of the difficulty of this geometry, the other repetitions of this scenario provided adequate separation. An important factor to be considered in the St. Louis scenario is the potential impact of the traffic advisory logic. Had the logic been in effect, a traffic advisory would have been displayed for a considerably long period of time, even before the turning maneuver was begun.

8.4.5 Unequipped Intruder Scenarios Not Able To Be Resolved By BCAS

As was stated in the early sections of this report, it is unrealistic to expect a collision avoidance system to protect against an unequipped intruder with a large vertical rate in every midair scenario. Two of the midairs modelled in this analysis fall into this category. In performance level 4, scenario G (Urbana, Ohio) fails to achieve 100 feet vertical and 1,000 feet horizontal separation for the majority of its encounters. In performance level 5, scenario C (Carmel, New York) and its inverse, scenario F, fail for many encounters.

8.4.5.1 The Urbana Midair Collision Simulation

Figure 8-26 is an individual characteristic plot of a typical failure encounter for the first of these two scenarios. The plot shows scenario 'G' which occurs in Urbana, Ohio, and involves a level BCAS equipped aircraft and an unequipped intruder. The intruder begins a 3,500 fpm descent at time 42 as shown in the top plot. At this time, the aircraft are separated by 1,400 ft vertically. Nine seconds later, the intruder



*SCANS SHOWN EVERY 4 SECONDS

FIGURE 8-25
HORIZONTAL GEOMETRY OF ST. LOUIS MIDAIR COLLISION

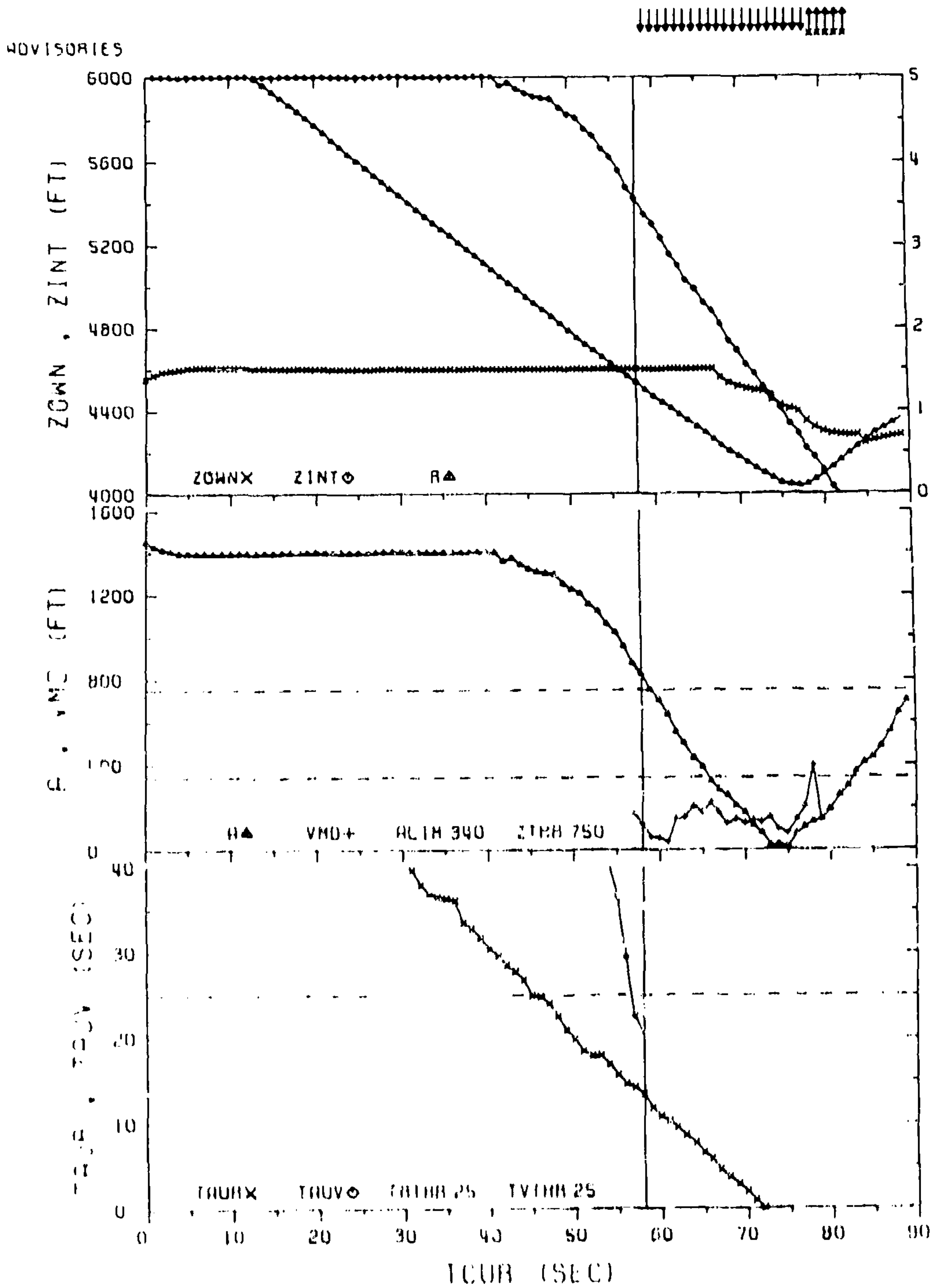


FIGURE 8-28
SEPARATION, TAU PLOTS FOR SCENARIO G .N PERFORMANCE LEVEL 4 (AN UNSUCCESSFUL RESOLUTION)

initiates a turn toward the BCAS aircraft. The BCAS logic selects a DESCEND for the BCAS aircraft at time 59, when both the range and altitude criteria are satisfied. Although extra warning time is provided by the unequipped intruder logic, the BCAS aircraft is eventually overtaken by the intruder. The tracked vertical rate of the unequipped intruder at the time of sense selection was approximately 2,300 fpm. The tracker had not yet caught up with the intruder's true rate of 3,500 fpm. Based on this inaccurate data, the selection of a DESCEND was predicted to provide greater separation at closest approach than a CLIMB.

Figure 8-27 shows an example of how tracker lag affects sense selection. The sense selection algorithm for an unequipped intruder with a vertical rate projects the altitude of the BCAS aircraft ahead by the amount of time left until closest approach. A maneuver delay time is accounted for. Both a climb and descend are modelled for the BCAS aircraft by using either the current climb or descent rate of the aircraft, or 1,000 fpm, whichever is greater in magnitude as the projected escape rate. A projection of the intruder's altitude is also made for the escape time available, by assuming that the intruder's current vertical rate will be maintained. The sense which provides the greatest altitude separation between the two aircraft at closest approach is selected.

When the tracked vertical rate of the intruder aircraft is inaccurate, the projected altitude of the intruder at the time of closest approach can be significantly in error. This is particularly true in high vertical rate scenarios. The plots in Figure 8-27 illustrate the difference in the predicted separation at closest approach for a climb and descend maneuver by the BCAS aircraft. The bottom plot shows that a tracked descent rate of 2,300 fpm projected ahead for 20 seconds, displaces the intruder's current altitude by 767 feet. However, the top plot shows that a true rate of 3,500 fpm, projected ahead for 20 seconds displaces the intruder's altitude by 1,167 feet, a 400 foot difference. Whereas a descend is predicted to provide much greater separation than a climb when the tracked rate is used, a climb is shown to significantly improve separation when the true rate is used.

It was shown in Section 8.4.3.1 that supplying the true altitude rate to the BCAS logic in place of the alpha beta tracker altitude rate data did not significantly improve the separation results for performance level 3 scenarios. It would appear, however, that for accelerating scenarios, accurate altitude rate data could have a substantial effect on separation for the

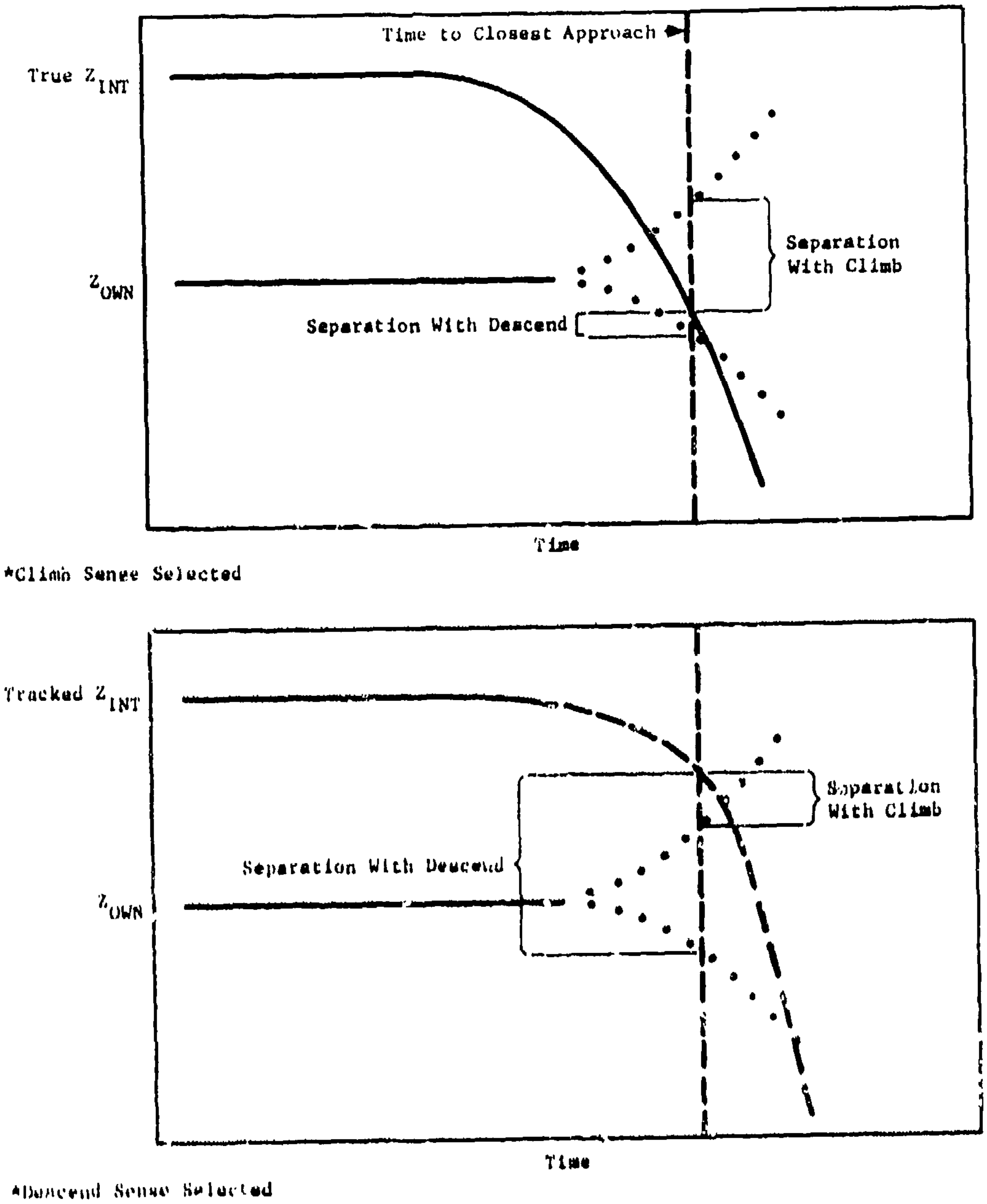


FIGURE 8-27
EFFECT OF TRACKER LAG ON SENSE SELECTION

Urbana scenario by causing a climb sense to be selected. The scenario was therefore rerun using perfect altitude rate data. Although some additional vertical separation resulted from a positive alert being displayed a few cycles earlier, the escape maneuver provided only marginal protection. The reason for this is that a descend was again selected as the displayed alert, and a descend for this scenario does not provide adequate separation.

It is important to understand why perfect altitude rate data does not satisfactorily improve the outcome of this scenario. According to the National Transportation Safety Board report, the vertical rate of the maneuvering aircraft was varying during the 40 seconds prior to collision. For the purposes of this simulation, a 1/8 g acceleration was assumed. Although this may not be entirely accurate, the varying vertical rate will cause the same effect, whether or not the 1/8 g is accurate. Figure 8-28 is an illustration of the sense selection outcome using perfect altitude rate data. It takes 15 seconds for the intruder to achieve a 3,500 fpm descent rate, accelerating at 1/8 g. However, the intruder is declared a threat by the logic after only 11 seconds into the maneuver. Therefore, at the time of sense selection, the intruder aircraft's vertical rate has not reached its peak because the aircraft is still accelerating. The vertical rate which is used to compute intruder's altitude at the time of closest approach, while accurate at that cycle, has only reached 2,735 fpm. That rate is not enough to predict that a climb will result in greater separation than a descend.

The intruder was descending at more than three times the rate of the BCAS aircraft only 13 seconds prior to closest horizontal approach. The only chance for the BCAS aircraft to satisfactorily resolve this conflict is to out-maneuver the intruder. This is much more likely to occur with a climb maneuver than a descend. More accurate vertical rate tracking should be an aid in providing better separation protection in many encounters because it will reduce the time frame in which an incorrect sense can be selected. However, it will not always be able to provide the most effective maneuver.

It must be noted (see Figure 8-26) that even with a TVTHR of 30 seconds, only one second of additional warning time would have been provided. Increasing the TVTHR value would not have provided satisfactory resolution for this conflict. Equally as important, using a larger TVTHR in an attempt to provide more protection would cause the number of unnecessary alerts in the performance level 4 region to rise. There is, therefore, no justification for increasing TVTHR above 25 seconds in this case in an effort to achieve better protection.

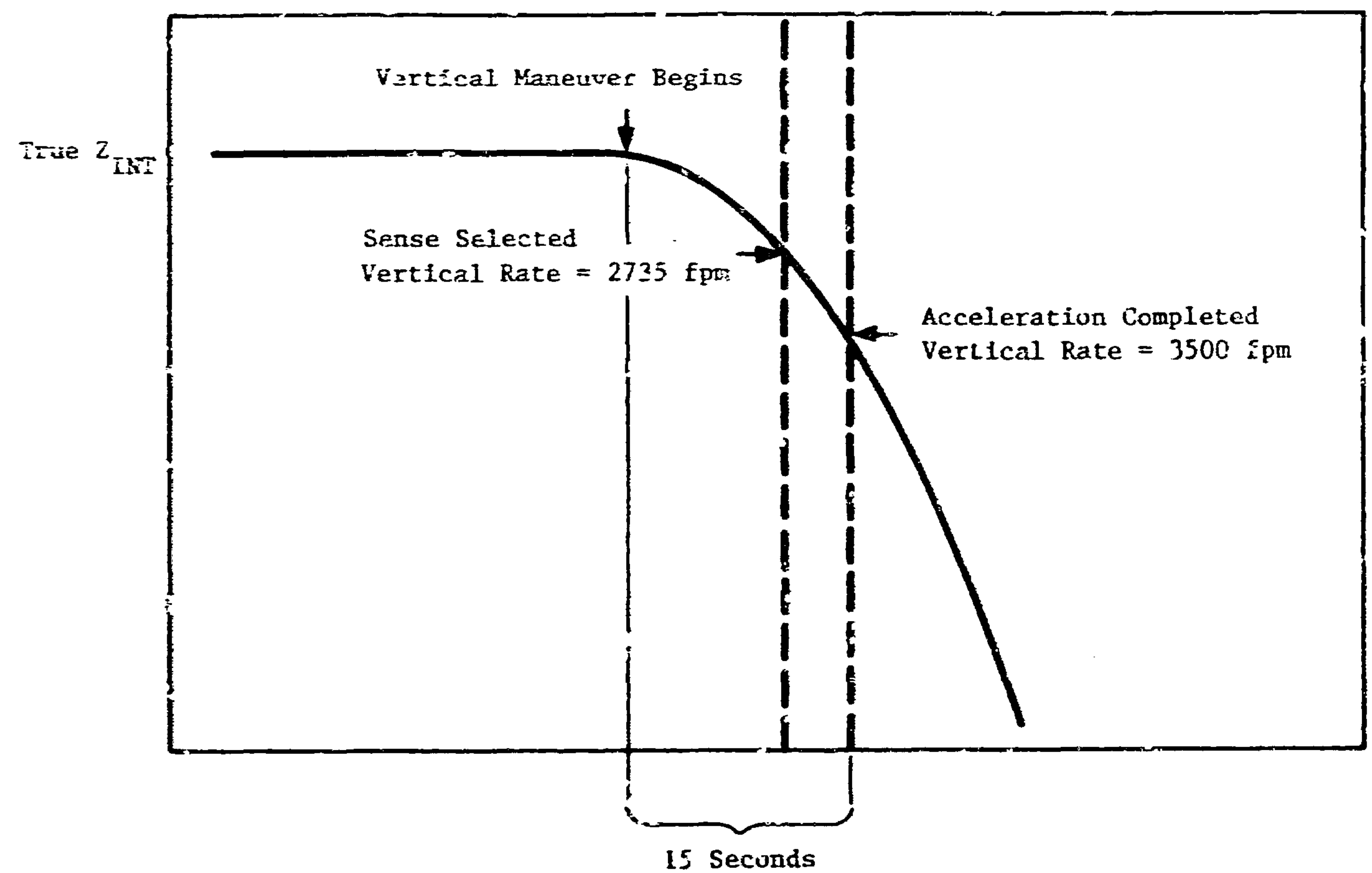


FIGURE 8-28
EFFECT OF EARLY SENSE SELECTION DUE TO PERFECT ALTITUDE RATE TRACKING

An additional twenty repetitions of scenario 'G' were made to analyze the effect of forcing the logic to select a climb sense for each encounter. In order to artificially cause a climb to be selected, the climb rate parameter used to model the vertical displacement of the BCAS aircraft at closest approach was made extremely large, while the descent rate parameter was zeroed. In addition, the acceleration rate parameter was also unrealistically increased. As a result, for these tests, the BCAS logic always predicted that a climb would provide more separation than a descend, without regard to the tracked vertical rate of the intruder.

Figure 8-29 shows the separation results when a climb sense is selected for each repetition. Without exception, separation achieved was greater than 150 feet. The nominal escape rates were used in this run. The outcome of this simulation run shows that scenario 'G' is not unresolveable by the BCAS logic. However, its successful resolution is hindered by the joint effects of a high vertical rate maneuver and a slow change in vertical rate.

Use of the nominal escape parameters proved ineffective in a descent maneuver away from the intruder aircraft. However, increasing the escape rate and acceleration used in a descent maneuver and decreasing the pilot response delay can significantly improve the separation for this scenario. Figure 8-30 is a scatter plot of 20 repetitions of scenario 'G' using nominal parameters in the bottom plot and using an escape rate of 1,500 fpm, acceleration of 1/2 g and response delay of 4 seconds in the top plot. Although the results are not as good as those shown in Figure 8-29, improvement in separation is evident. Displacement increased by nearly 100 feet for most encounters. These results demonstrate that the problems caused by sudden large vertical maneuvers by an unequipped intruder can often be overcome by greater escape performance on the part of the BCAS equipped aircraft.

Another important factor in this scenario is equipage. Scenario 'G' is simulated with a Beechcraft Baron equipped with BCAS, while the intruder, a DC-9, is unequipped. This is not representative of a likely equipage configuration. It is more likely that the high performance DC-9, which was the aircraft initiating the high vertical rate maneuver, would be equipped -- scenario B. The results for the inverse condition simulating the DC-9 as equipped ('B' in Figure 8-14), show that significantly better separation is achieved. In this situation, it is the BCAS aircraft which has the large vertical rate. An evasive maneuver by the higher performance aircraft results in better separation.

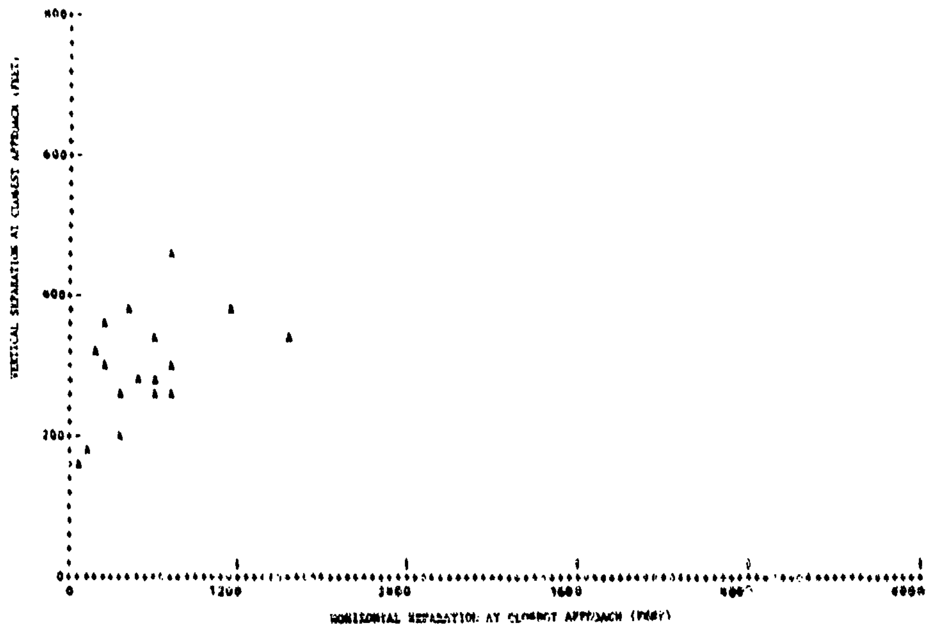
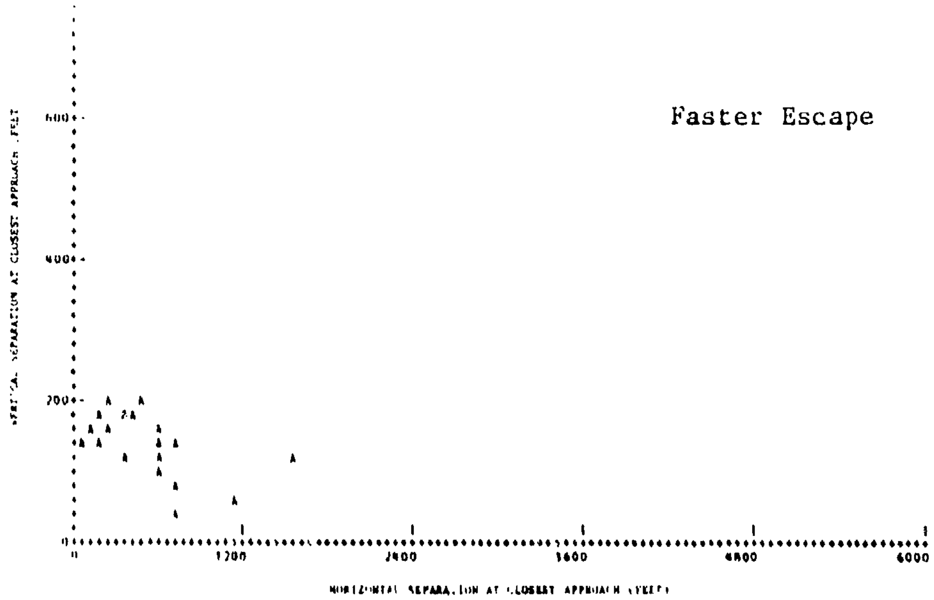


FIGURE 8-29
CLOSEST APPROACH WITH ONE UNEQUIPPED FOR 20 REPETITIONS OF SCENARIO G IN PERFORMANCE LEVEL 4 WHEN ARTIFICIALLY FORCING A CLIMB



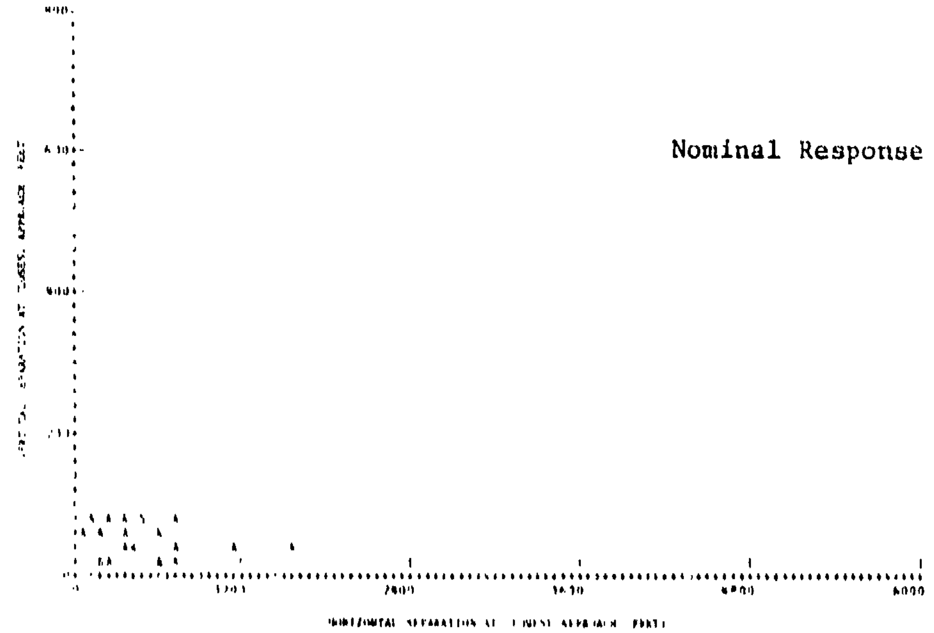


FIGURE 8-30
COMPARISON PLOTS OF NOMINAL RESPONSE VERSUS FASTER ESCAPE RATES (URBANA, OHIO)

8.4.5.2 The Carmel Midair Collision Simulation

Figure 8-31 shows a failure encounter of scenario C occurring in Carmel, N.Y. in performance level 5. The tracked altitudes of the BCAS and intruder aircraft are 10,000 and 11,100 feet respectively. At time 106, the unequipped intruder abruptly begins a climb of 4,000 fpm toward the level BCAS aircraft. At that time, the aircraft are separated in altitude by only 900 feet (tracked altitude difference is shown to be greater than 1,100 feet). Range separation is less than one nmi. At time 115, a DON'T DESCEND is displayed. At the very next scan, the projected vertical separation (VMD) falls below ALIM to trigger the unequipped intruder logic. A positive CLIMB should be displayed to own aircraft. However, for these simulations the BCAS logic contains a time out requirement which suppresses any new alerts until the previous alert has been displayed for 5 seconds. As a result, the climb is not displayed until scan 120, just one second before closest approach. The timing out of alerts is currently an issue to be resolved in the BCAS logic and is discussed in Section 8.4.5.3. For this particular encounter, however, an instant update of alerts would probably not have significantly improved the outcome. (Closest approach was 404 feet in range and 1 foot in altitude.) A rate of 4,000 fpm requires only 13 seconds to pass through 900 feet and reach coaltitude. In addition, the relatively high closing rate and low escape rate are factors which truly hinder BCAS performance in this scenario as well as its inverse, scenario F.

Note again that increasing TVTHR even to 60 seconds would not have satisfactorily resolved this conflict. The additional 2 seconds which would have been provided could not have prevented this encounter from failing.

There is another important consideration to be weighed with respect to the Carmel and Urbana scenarios. The logic which detects and displays traffic advisories has not been simulated for this study. However, it is interesting to know whether or not a traffic advisory would have been displayed for either scenario, and how soon before the collision the advisory would have been displayed. A hand check of the logic as it existed in the modification to Reference 7 (January 80 logic) showed that a traffic advisory would have been displayed against the intruder for both scenarios. For the Carmel, N.Y. accident (C), the advisory would have been displayed at about scan 70, when the aircraft were separated in range by more than 7 nmi, well in advance of the BCAS advisory, which appeared at scan 115, when range separation was less than 2 nmi. The traffic advisory logic for a conflict in performance level 5 uses a 45 second TRTHR, 1.2 nmi DMOD and an immediate relative altitude threshold

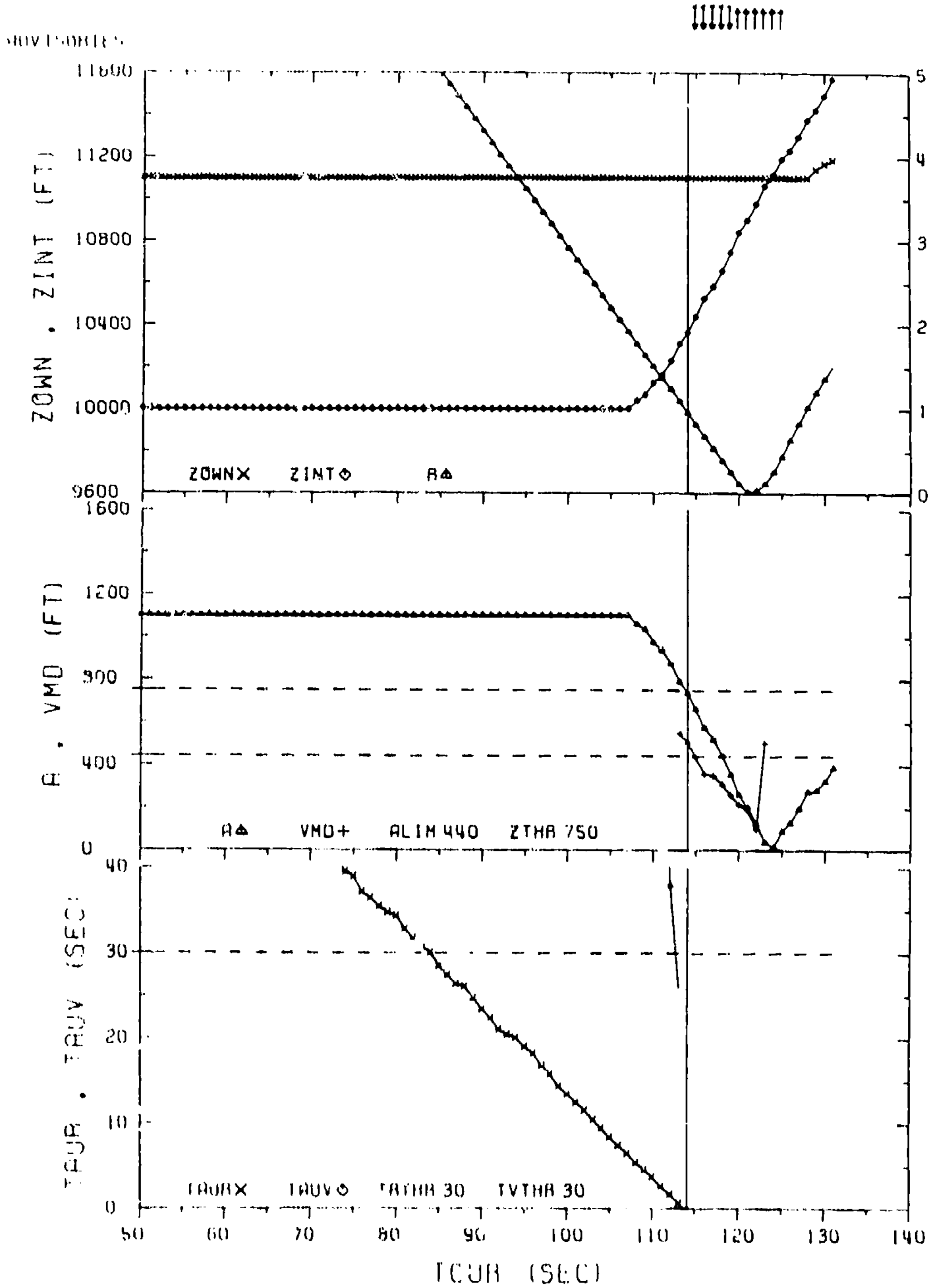


FIGURE 8-31
SEPARATION, TAU PLOTS FOR SCENARIO C IN PERFORMANCE LEVEL 5 (AN UNSUCCESSFUL RESOLUTION)

of 1,200 ft. Since the relative altitude difference from the beginning of this scenario was only 1,100 feet, as soon as the range criteria is satisfied, the advisory will be displayed. If this advisory had actually been displayed to the pilot of the aircraft initiating the abrupt maneuver, showing the correct altitude of the traffic, it is conceivable that this accident could have been averted.

The timing of a traffic advisory in the Urbana, Ohio scenario (G) would not have been as beneficial as in the Carmel accident. The thresholds for an advisory in performance level 4 are a TRTHR of 40 seconds, a DMOD of 0.4 nmi and the same immediate altitude threshold of 1,200 feet. Because the aircraft are separated by nearly 1,500 feet, the range criteria will not satisfy the advisory logic until the altitude separation falls below 1,200 feet. This occurs at scan 53, when the range difference is only about 1.75 nmi. This precedes the BCAS resolution advisory by only six seconds, but may serve to shorten the pilot reaction time to that advisory.

While a traffic advisory is not equivalent to a BCAS alert, it can have a very useful effect on the pilots of aircraft in conflict. A pilot who is aware of the existence of a threat aircraft may be able to acquire the threat visually and be better able to detect a sudden maneuver in time to take evasive action. More importantly, the pilot of a BCAS equipped aircraft can avoid initiating a dangerous maneuver by first checking his traffic advisory display. In the case of the Carmel accident, an unnecessary, hazardous maneuver might have been avoided.

8.4.5.3 Timing Out of Commands

An issue which has surfaced in the Monte Carlo simulation runs is whether or not the BCAS logic should require an alert to be displayed for a specific number of scans before allowing a new alert to take its place. This issue pertains only to alert changes of increasing severity, i.e., a VSL to a negative, or a negative to a positive.

Several encounters were found in which the first alert choice was valid for only a cycle or two. Then a new condition would arise, requiring a more severe advisory. Satisfactory resolution of these encounters was hindered due to the time out logic. Only after an advisory had been in effect for 5 consecutive cycles could the new advisory be displayed. In addition, the Monte Carlo program would then model response delay to the new alert before a maneuver was initiated.

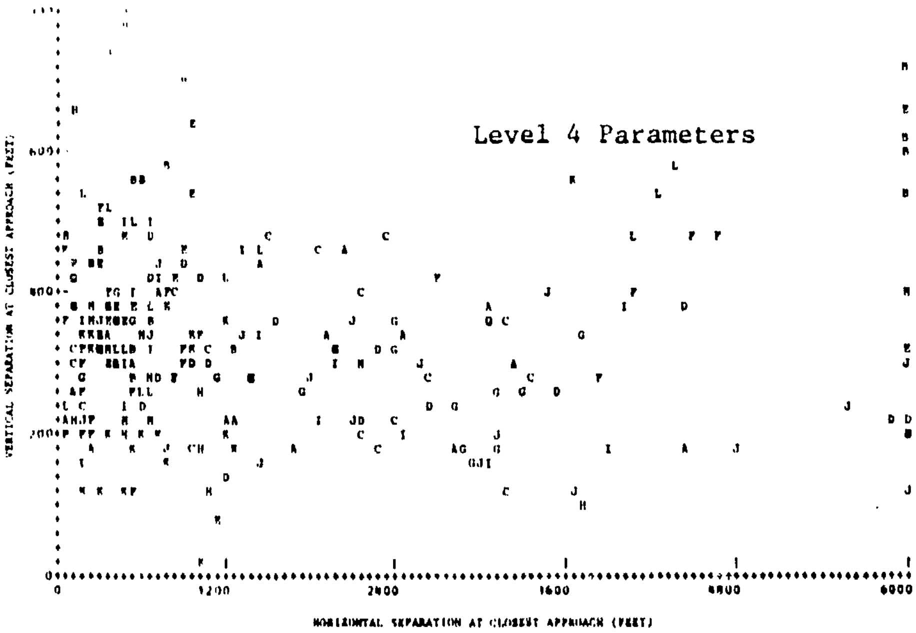
Monte Carlo results indicate that the time out logic should be eliminated for alerts increasing in severity. However, before displaying less severe alerts, the time out logic should be satisfied first.

8.5 Protection Tradeoffs Between Performance Levels

In order to assess the impact that performance level threshold values have on real midair data, each of the three midair groups was rerun using a performance level other than its nominal one.

Figure 8-32 shows a comparison of the nominal performance level 3 run (bottom plot) and a run of the performance level 3 scenarios using performance level 4 parameters with one aircraft unequipped (top plot). This plot addresses the basic issue of this entire study. The baseline BCAS logic prior to this study suggested values for TRTHR and DMOD of 25 seconds and 0.3 nmi, respectively. The Houston results presented earlier suggested that in the performance level 3 region, the values should be reduced to 20 seconds and 0.1 nmi. Comparison of the two plots shows directly how much collision protection is given up in making these parameter reductions. As expected, the separation achieved at closest approach significantly increased as a result of using the larger thresholds. In particular, the critical area between 200 feet in altitude and 1,000 feet in range was cleared very effectively. Increased parameter values affected the horizontal as well as vertical spread. The plot shows that only scenario K fails to achieve 200 feet vertical separation for more than one encounter. Also note that not a single encounter falls short of 100 feet vertical separation, within 1,000 feet in range.

This scatter plot viewed out of context, can provide a negative feeling about the merits of performance level 3 parameters. However, it is important to consider the consequences if performance level 3 were to be replaced by performance level 4. The alert rate would increase dramatically, in fact, Houston data statistics show that the alert rate would more than double. This brings with it a high incidence of unnecessary and distracting alerts for pilots in the TCA. Moreover, those alerts present with level 4 parameters and not present with level 3 parameters would be the alerts most likely to be considered unnecessary alerts by pilots. The most important effect of eliminating performance level 3 and implementing only performance level 4 is that BCAS would have to be disabled much farther from the airport than the recommended 2 nmi in order to control unnecessary alerts. Using performance level 3 parameters in the near vicinity of an airport provides the least disruption to normal procedures while ensuring the greatest pilot/controller area of protection for BCAS equipped aircraft.



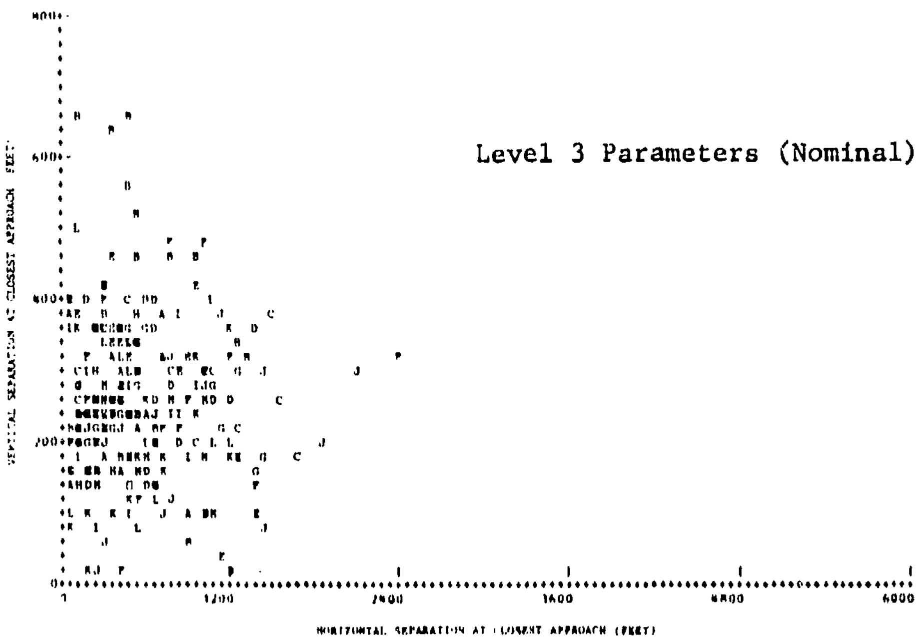


FIGURE 8-32
COMPARISON OF PERFORMANCE LEVEL 3 SCENARIOS RUN WITH LEVEL 3 VERSUS LEVEL 4 PARAMETERS

Figure 8-33 shows a comparison of the nominal performance level 4 run (bottom plot) and a run of performance level 4 scenarios with performance level 3 parameters (top plot). Not unexpectedly, separation at closest approach decreased as is evident in comparing the top and bottom plots. Scenarios G and C had several failures when run with the appropriate performance level 4 parameters. However, additional failure scenarios such as A, B and J were introduced by lowering parameter values. These results show that it is not advisable to eliminate performance level 4 in favor of using performance level 3 except where necessary to control the unwanted alert rate. (In fact, previous discussion concerning the possibility of extending the range boundary between performance levels 3 and 4 beyond 10 nmi from an airport does not seem plausible either.) The midair simulations corroborate the need for a range boundary in the general region of 10 nmi from an airport.

Finally, Figure 8-34 shows a comparison of the nominal performance level 5 run (bottom plot) and a run of performance level 5 scenarios run with performance level 4 parameters (top plot). While both horizontal and vertical separation were noticeably reduced, few encounters were added to the critical zone. Instead, a few scenarios which had provided more than adequate protection before, are provided separation of only borderline effectiveness with decreased parameters.

The performance level 5 data confirms what has been learned from close analysis of individual failure encounters. The most difficult scenarios for BCAS to protect against in unequipped intruder encounters are those where the intruder initiates an abrupt vertical maneuver to a high vertical rate. Increasing the warning time parameters in these cases is not very effective in providing additional protection.

8.6 Comparison of Response Time and Escape Rates

Pilot and aircraft response times, climb/descend rates and acceleration rates are all extremely important variables in separation assurance. However, while response delay and aircraft performance may be the determining factor as to the success or failure of a BCAS alert, they are variables over which the BCAS logic itself has no direct control.

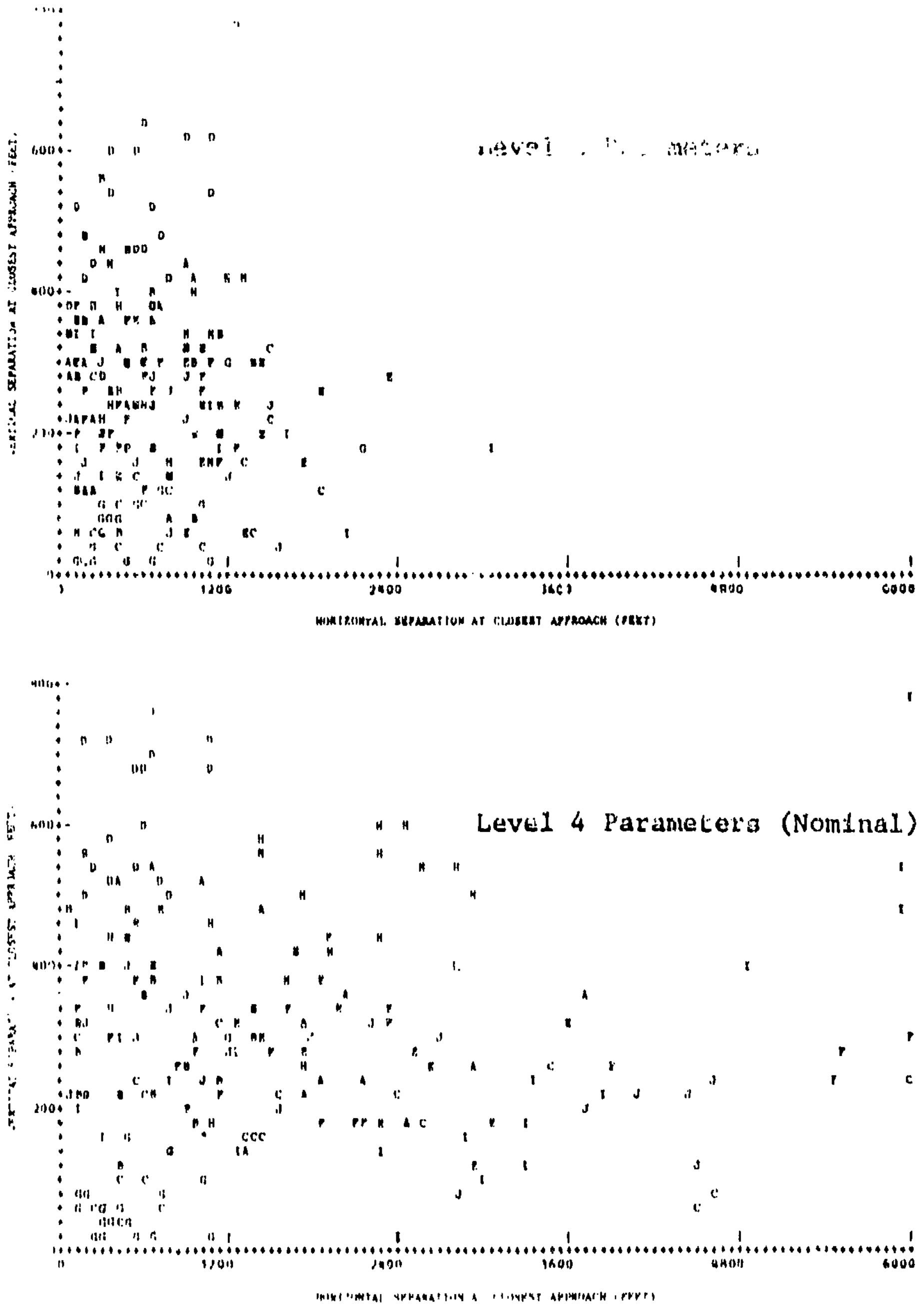
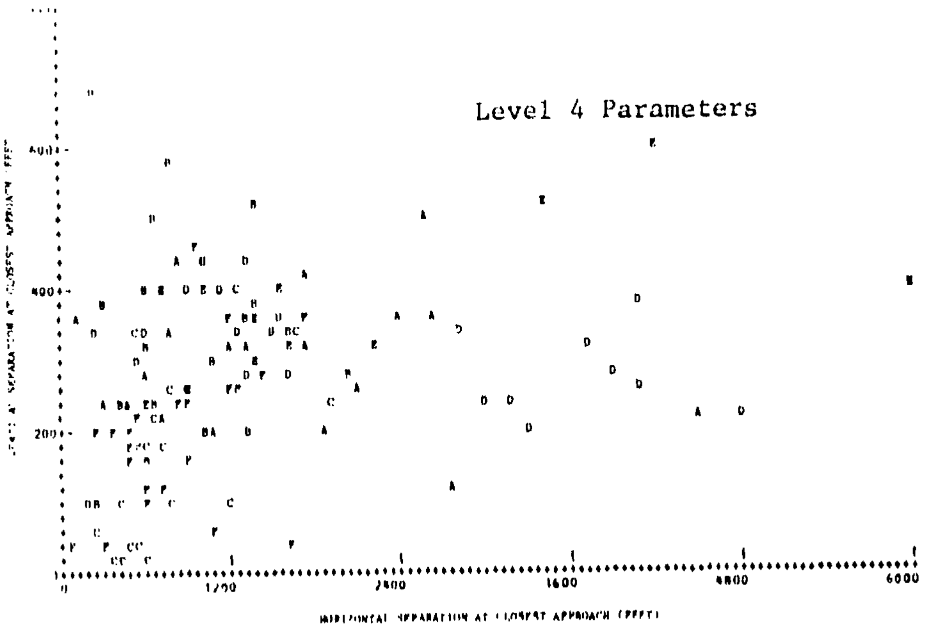


FIGURE 8-33
COMPARISON OF PERFORMANCE LEVEL 4 SCENARIOS RUN WITH LEVEL 4 VERSUS LEVEL 3 PARAMETERS



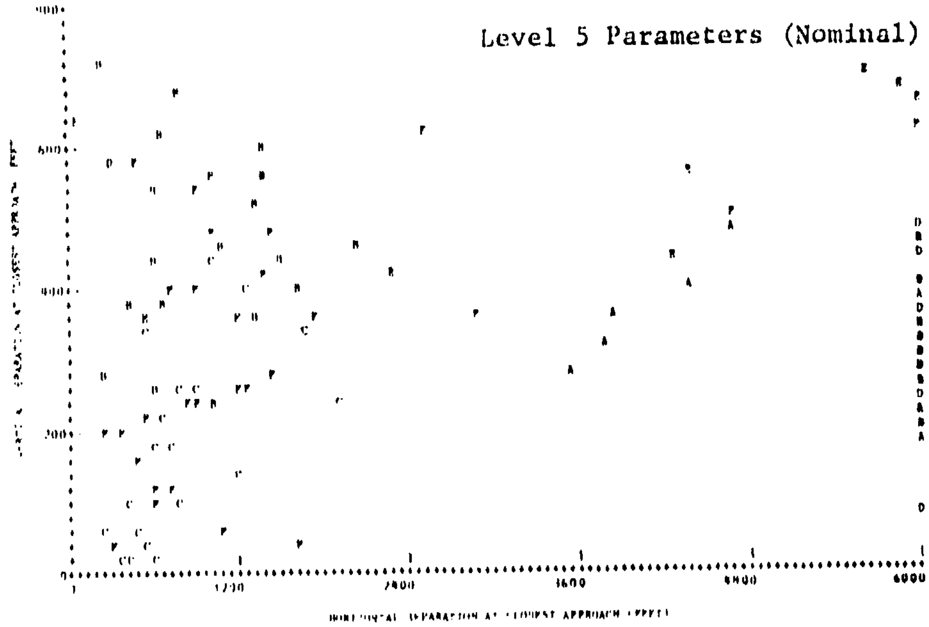


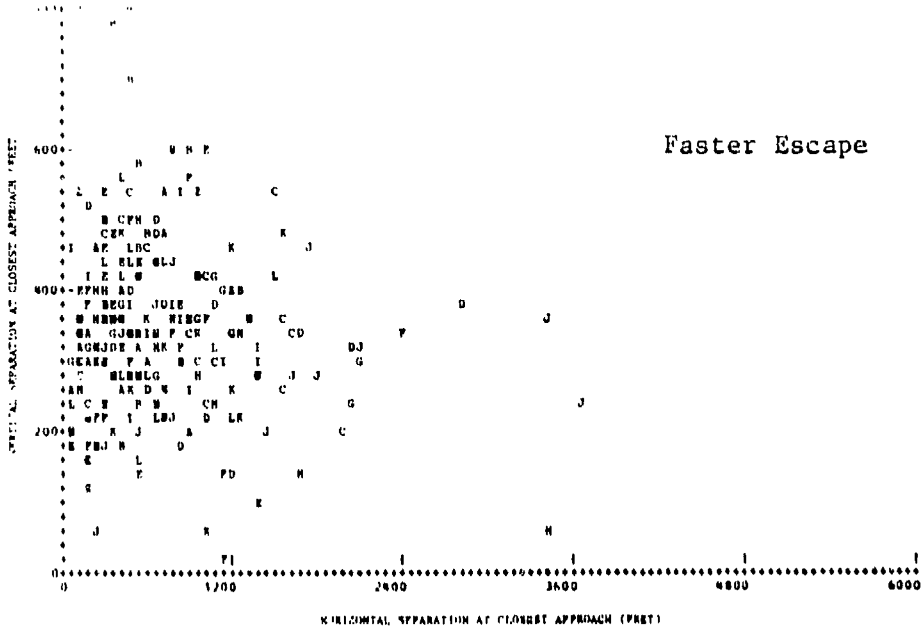
FIGURE 8-34
COMPARISON OF PERFORMANCE LEVEL 5 SCENARIOS RUN WITH LEVEL 5 VERSUS LEVEL 4 PARAMETERS

8.6.1 Increased Response Simulation

In order to emphasize the signficance of the aircraft response variables, additional runs of the midair sets were analyzed using different response and escape models. Those values used for the original simulation runs may be considered conservative. Figure 8-35 shows scatter plots of performance level 3 scenarios run against an unequipped intruder. This was the region which produced the most failures with the nominal pilot and aircraft response model. For the run presented on the top in Figure 8-35, the average pilot and aircraft delay time was reduced by one second to four seconds, the climb/descend rate was increased from 1,000 fpm to 1,500 fpm and the escape acceleration was increased from 1/3 g to 1/2 g. All other simulation characteristics remained at their nominal values. The plot on the bottom shows the run using nominal parameters.

Separation was significantly improved through more rapid and positive response for nearly every encounter, on the order of 150 feet of additional altitude separation. Only a few encounters remain in the critical zone. It is conceded that not all of the aircraft in this data base may be able to achieve a sustained 1,500 fpm climb or descend rate. However, the results presented here represent results when the response generates a vertical displacement of 383 feet (20 second alert time, 4 second delay, 1/2 g acceleration and 1500 fpm escape rate). Most aircraft likely to be carrying a BCAS can achieve this displacement through a combination of powered climb and a zoom maneuver, where airspeed is allowed to bleed off in exchange for an increase in altitude.

Even with increased response, three encounters resulted in less than 100 feet vertical separation. Each of these was reviewed in detail. The encounter labelled J was a failure due primarily to a particular feature in the logic called the vertical divergence feature. Initially, both aircraft were level and were truly separated by 44 feet with the BCAS aircraft above. However, due to altimetry errors, the unequipped intruder appears to be 200 feet above the BCAS aircraft. The BCAS aircraft received a DESCEND advisory. Seven seconds after the display of the DESCEND, the aircraft had responded, and based on the tracked descent rate, the logic predicted a safe separation. The advisory then changed to a DON'T CLIMB and the BCAS aircraft levelled off. At this point, the BCAS aircraft had only descended 99 feet. After some time, the tracker responded to the level off and the logic no longer predicted a safe separation. It again generated a DESCEND advisory, but by the time the pilot responded, the closest approach had occurred. The major effect causing this failure was that the



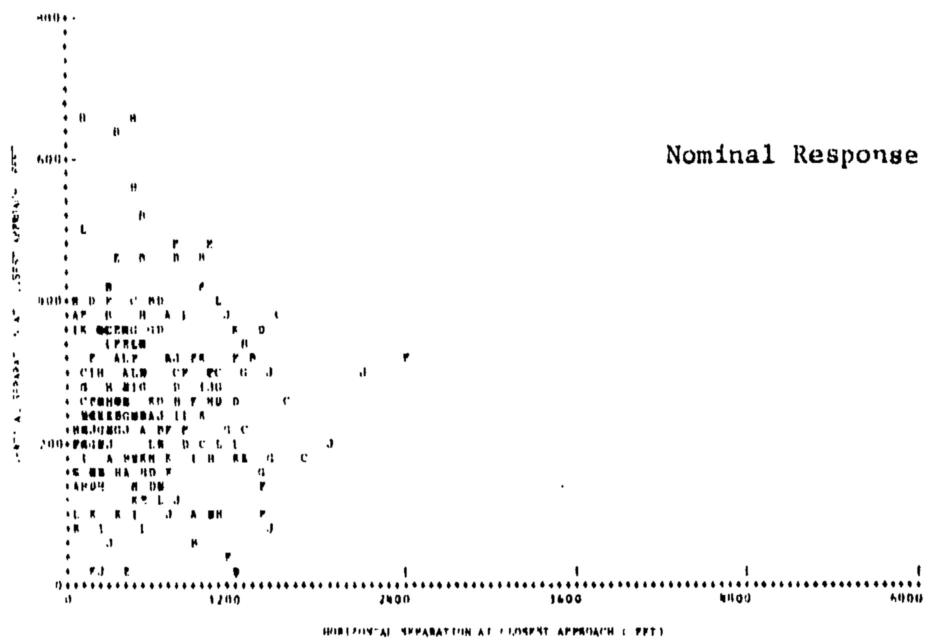


FIGURE 8 35
COMPARISON PLOTS OF NOMINAL RESPONSE VERSUS FASTER ESCAPE RATES (PERFORMANCE LEVEL 3—ONE UNEQUIPPED)

vertical divergence feature of the logic permitted the DESCEND to transition to a DON'T CLIMB prematurely.

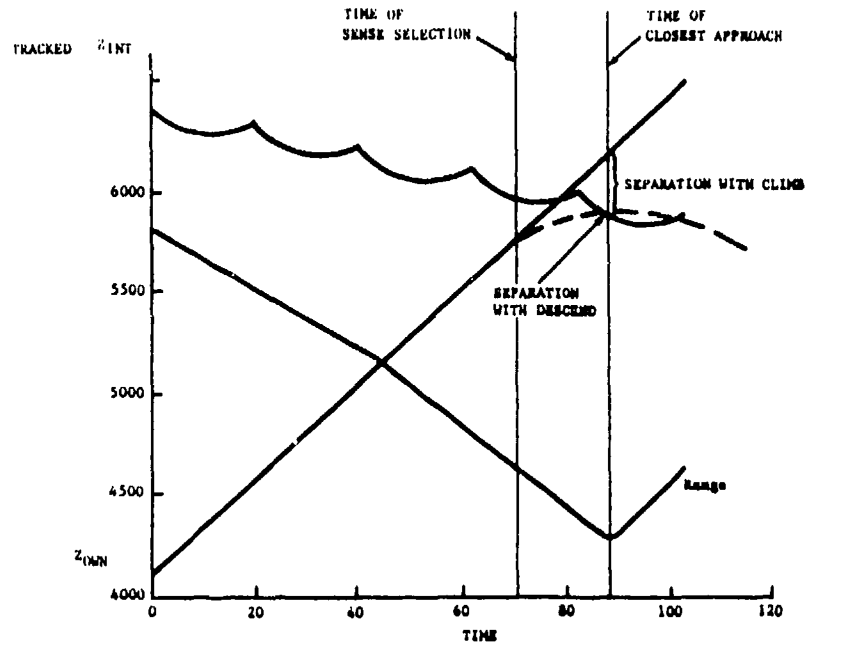
The exact same encounter was rerun when the DESCEND advisory was artificially forced to remain displayed. In this run, 244 feet of vertical separation was achieved at closest approach. The combined altimetry errors also contributed to the difficulty, but were not the major cause of the failure. If the altimetry errors had been zero, the DESCEND advisory would have remained displayed for a longer time, and safe separation would have been achieved. Also, even though the altimetry errors in this case created what technically could be called an altitude crossing maneuver, the BCAS aircraft only had to maneuver through 55 feet to overcome the error. This small altitude crossing situation was easily overcome when the DESCEND remained displayed. This feature, which allows a positive advisory to transition to a negative prematurely, has been put on the list of BCAS logic issues and will be corrected. The scenario J failure therefore will be eliminated and should not be counted as a failure due to altimetry errors.

The scenario labelled K is a failure due to the same cause as scenario J -- the positive advisory transitioned to a negative advisory prematurely. Again, this failure will be eliminated.

The scenario labelled E is a failure due to an altitude crossing maneuver caused by altimetry errors. This scenario is the same as scenario K except that the equipage roles are reversed. Figure 8-36 is plot showing true versus tracked altitudes for this encounter. The BCAS aircraft is climbing at 1430 fpm while the unequipped intruder is descending at 300 fpm. At the time of alert, the BCAS logic selects a CLIMB advisory for the BCAS aircraft because it predicts that 385 feet of vertical separation would result from a CLIMB and 125 feet separation would result from a DESCEND. If the BCAS logic had not been subjected to a relative altitude error of 290 feet, it would have predicted 95 feet separation from a CLIMB and 415 feet separation from a DESCEND and would clearly have selected the DESCEND. The BCAS aircraft, in response to the CLIMB advisory, increased its climb rate from 1430 fpm to 1455 fpm, but this had only an insignificant effect on the separation at closest approach.

8.6.2 Decreased Response Simulation

The improvement offered by the run described above is in stark contrast to Figures 8-37 through 8-39. These three comparison scatter plots represent the separation which results when pilot response time is fixed at 10 seconds for every encounter (top



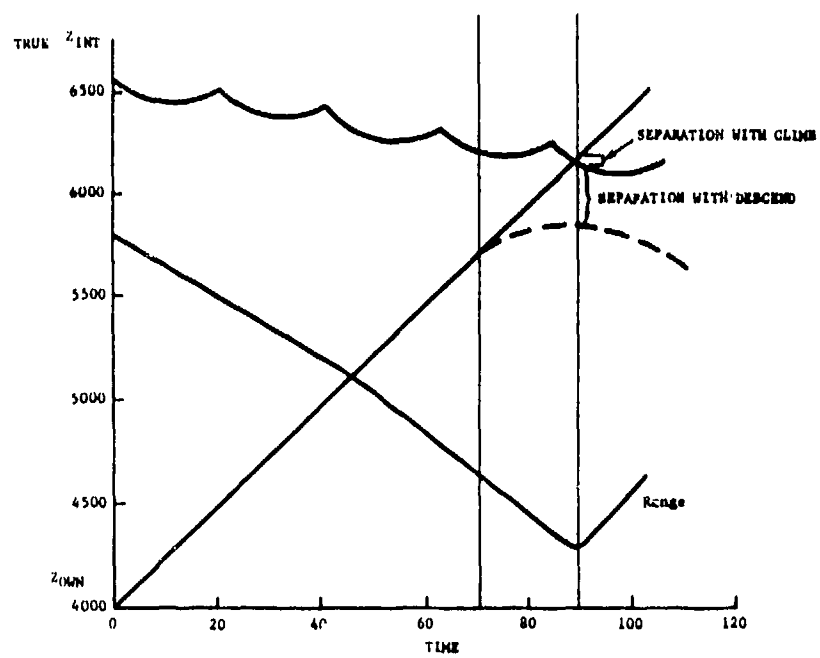


FIGURE 8-36
SEPARATION PLOT FOR SCENARIO E IN PERFORMANCE LEVEL 3
(AN UNSUCCESSFUL RESOLUTION DUE TO ALTIMETRY ERROR)

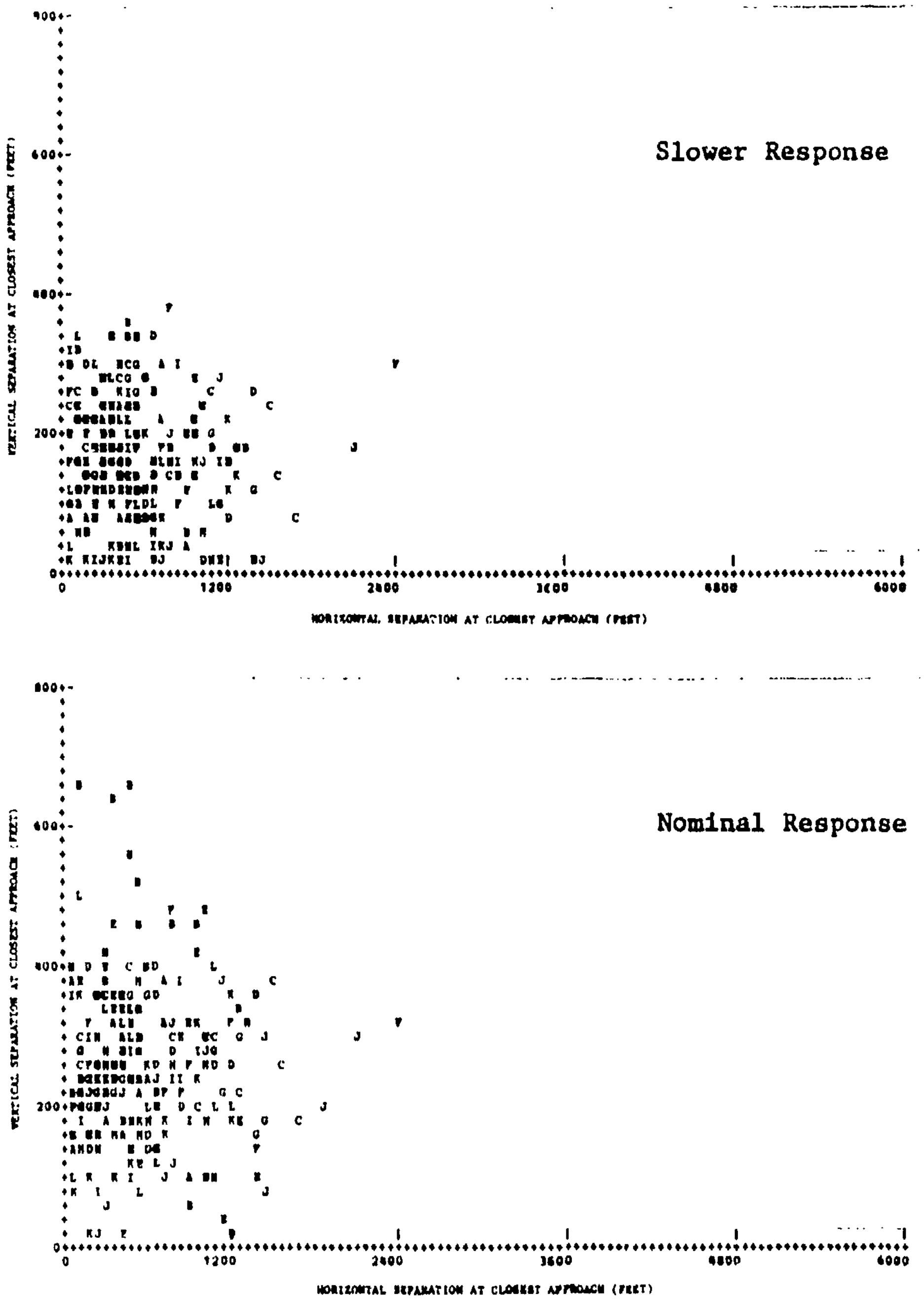


FIGURE 8-37
COMPARISON OF NOMINAL RESPONSE VERSUS SLOWER RESPONSE TIME (PERFORMANCE LEVEL 3 SCENARIOS—ONE UNEQUIPPED)

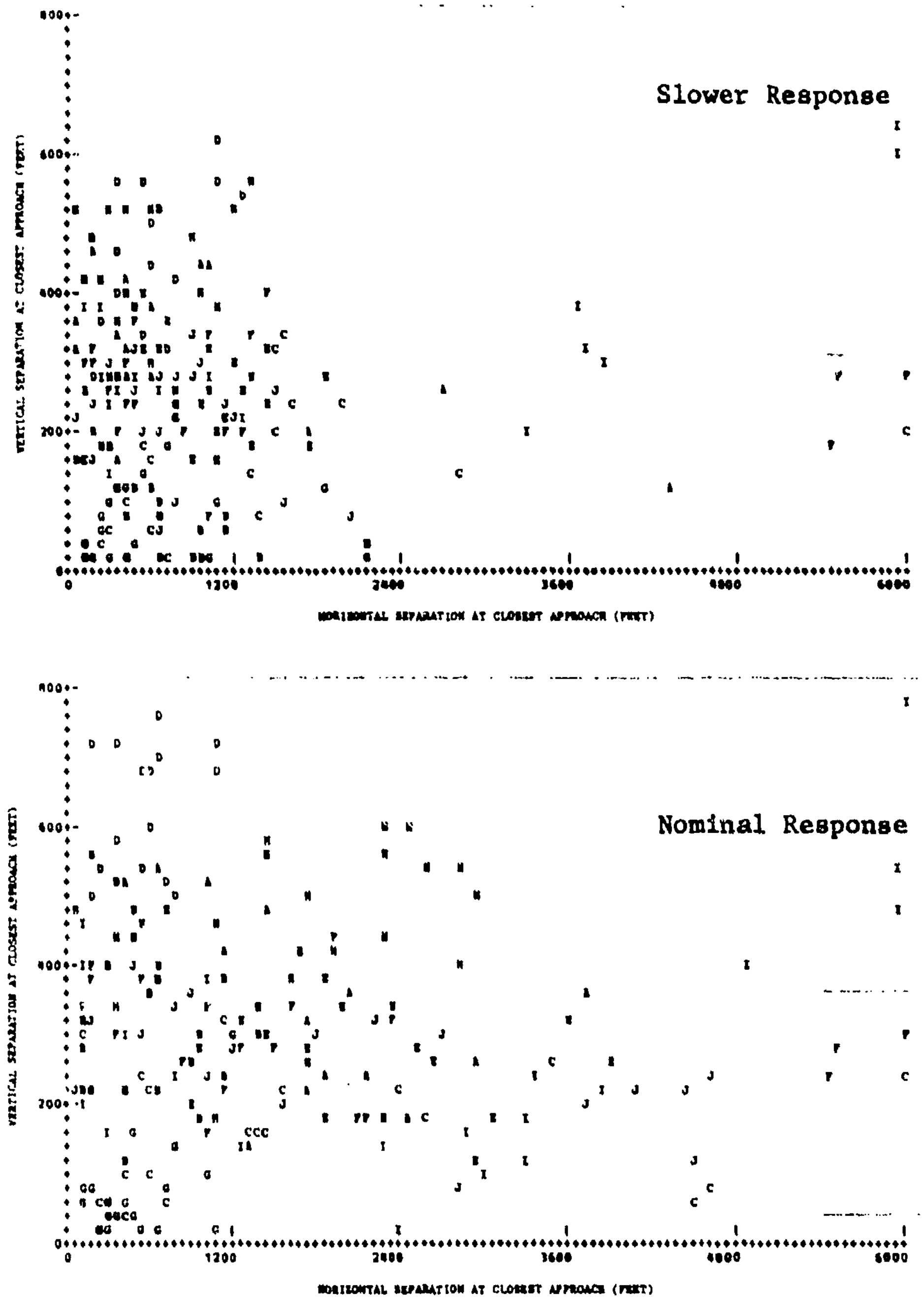


FIGURE 8-38
COMPARISON OF NOMINAL RESPONSE VERSUS SLOWER RESPONSE TIME (PERFORMANCE LEVEL 4 SCENARIOS—ONE UNEQUIPPED)

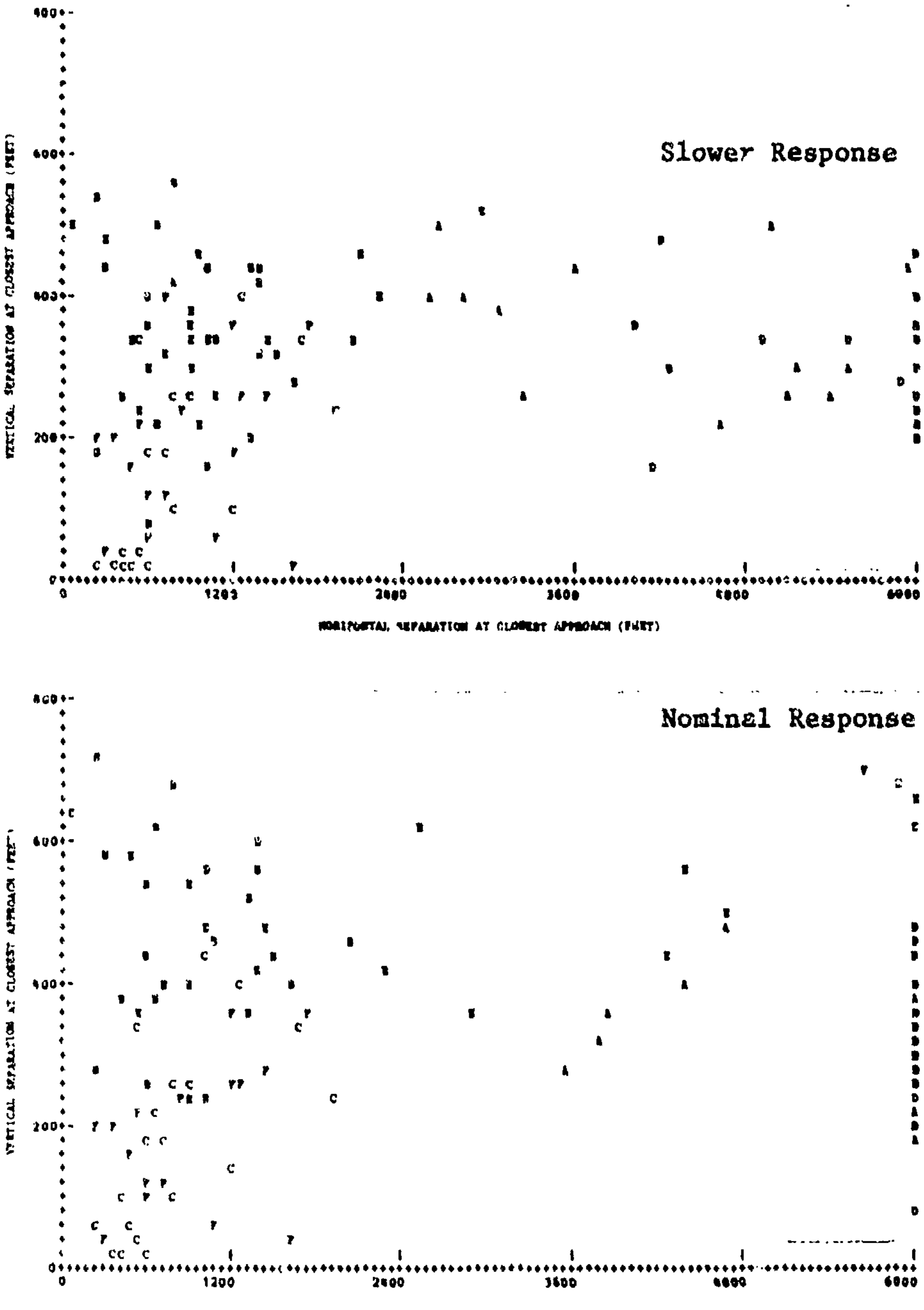


FIGURE 8-39
COMPARISON OF NOMINAL RESPONSE VERSUS SLOWER RESPONSE TIME (PERFORMANCE LEVEL 5 SCENARIOS—ONE UNEQUIPPED)

plots) versus the nominal runs for each performance level (bottom plots). No increase in escape rates beyond the nominal values were used. The results are particularly discouraging for the performance level 3 region, although each region was affected to some degree. The key to BCAS separation protection lies in pilot and aircraft response. BCAS is meant to be a quick response collision avoidance system.

8.7 Summary of Protection Tradeoffs

The combination of real world radar data and simulated reconstructions of actual midair collisions has shown that a very real tradeoff exists between reducing the number of unnecessary alerts and providing adequate separation protection.

Simulating the reconstructed midairs in an 'error-free' environment showed that effective separation protection is provided by the BCAS logic. The introduction of real world errors into the simulation showed varying degrees of performance degradation. The major factor contributing to performance degradation was altimetry errors. However, nearly all of the scenarios that experienced poor resolution with the nominal simulation parameters did much better when increased escape rates and less response time were simulated, in spite of altimetry effects. The role of the pilot in providing the best escape possible is a crucial factor in BCAS performance.

A few of the critical scenarios were shown to achieve much better separation when the higher performance aircraft was simulated to be BCAS equipped as opposed to the situation when the low performance aircraft was equipped. Since it is most probable that high performance aircraft will be equipped first, simulating the reverse is often not very realistic.

It is important to look at the alternative to desensitizing logic parameters. Eliminating performance level 3 in favor of using performance level 4 everywhere below 10,000 ft MSL would result in a significant increase in the number of unnecessary alerts. The parameter values and boundary selections made for performance levels 3, 4 and 5 appear to be an effective compromise in meeting the goals of reducing unnecessary alerts and providing satisfactory separation protection.

APPENDIX A

RBX SITE SELECTION

A study was conducted for the FAA to estimate the number of RBX units that may be required to support a national implementation of Active BCAS.

Using information obtained from the Department of Transportation "FAA Air Traffic Activity" document, Fiscal Year 1978, a strategy for RBX site selection has been identified.

The strategy involves choosing those airports which report high traffic activity as plausible RBX sites. The only concrete basis for judging airport requirements is the Houston Study. It seems clear that an RBX is warranted at both Houston Intercontinental, which ranks 15th in air carrier operations, and Hobby airport, which ranks 76th. It is feasible then that any airport ranking higher than Hobby would also require an RBX. Initially, those towers ranking highest in annual air carrier operations were chosen. A cutoff point was designated to exclude those airports reporting fewer than 10,000 air carrier operations. The resulting ordered list consists of 150 of the 428 airports with FAA operated towers.

In addition to the highest ranking air carrier airports, a list of towers ranked by total aircraft operations was consulted in order to include a portion of large general aviation airports. From this list, the first 50 airports with towers which were not included in the top 150 air carrier airports were selected as additional RBX sites. Note that those airports ranking less than 356th have reported no air carrier operations. However, high performance general aviation aircraft in these busy airports would benefit from RBX installation. The 200 airports shown in Figures A-1 and A-2 are suggested candidates for RBX allocation.

A few examples of airports which would not be included under this hypothetical procurement of 200 RBX units are:

FAA-OPERATED AIRPORT TRAFFIC CONTROL TOWERS BY RANK ORDER OF AIR CARRIER OPERATIONS

TOWER	STATE ABBREV.	HUB	RANK	NUMBER
CHICAGO OHARE INTL	IL	L	1	590304
ATLANTA INTERNATIONAL	GA	L	2	484630
LOS ANGELES INTERNATIONAL	CA	L	3	375924
DALLAS FT WORTH REGIONAL	TX	L	4	311494
JOHN F KENNEDY INTL	NY	L	5	277332
DENVER STAPLETON INTL	CO	L	6	268586
LA GUARDIA	NY	L	7	268032
SAN FRANCISCO	CA	L	8	265720
MIAMI INTERNATIONAL	FL	L	9	245477
BOSTON LOGAN	MA	L	10	217792
WASHINGTON NATIONAL	DC	L	11	208417
PITTSBURGH GREATER INTL	PA	L	12	195022
ST LOUIS INTERNATIONAL	MO	L	13	190249
DETROIT METRO WAYNE CO	MI	L	14	162776
HOUSTON INTERCONTINENTAL	TX	L	15	160705
PHILADELPHIA INTL	PA	L	16	145662
MEMPHIS INTERNATIONAL	TN	M	17	140557
NEWARK	NJ	L	18	133304
CLEVELAND HOPKINS INTL	OH	L	19	131193
TAMPA INTERNATIONAL	FL	L	20	127988
MINNEAPOLIS ST PAUL INTL	MN	L	21	127036
KANSAS CITY INTERNATIONAL	MO	L	22	123260
SEATTLE TACOMA INTL	WA	L	23	117744
HONOLULU	HI	L	24	117663
LAS VEGAS MCCARRAN INTL	NV	L	25	112891
NEW ORLEANS MOISANT	LA	L	26	107422
PHOENIX SKY HARBOR INTL	AZ	L	27	99540
FORT LAUDERDALE	FL	L	28	84370
ORLANDO JETPORT	FL	M	29	83690
SAN DIEGO LINDBERG	CA	M	30	82955
PORTLAND INTERNATIONAL	OR	M	31	81271
BUFFALO INTERNATIONAL	NY	M	32	78395
INDIANAPOLIS INTERNATIONAL	IN	M	33	78326
CINCINNATI GREATER	KY	M	34	76226
SALT LAKE CITY INTL	UT	M	35	75222
BALTIMORE WASHINGTON INTL	MD	M	36	74410
MILWAUKEE MITCHELL	WI	M	37	72634
CHARLOTTE DOUGLAS	NC	M	38	67987
NASHVILLE METROPOLITAN	TN	M	39	63456
WINDSOR LOCKS	CT	M	40	62134
ANCHORAGE INTL RAPCON	AK	M	41	61099
SAN JOSE MUNICIPAL	CA	S	42	59464
LOUISVILLE STANDIFORD	KY	M	43	57487
SAN ANTONIO INTERNATIONAL	TX	M	44	57147
COLUMBUS INTERNATIONAL	OH	M	45	56487
WASHINGTON DULLES INTL	VA	L	46	55175
OKLAHOMA CITY WILL ROGERS	OK	M	47	52124
DAYTON	OH	M	48	50963
TULSA INTERNATIONAL	OK	M	49	49653
SAN JUAN INTERNATIONAL	PR	L	50	47783
OAKLAND INTERNATIONAL	CA	L	51	46990
OMAHA	NE	M	52	46840
ROCHESTER MONROE COUNTY	NY	M	53	45965
ALBUQUERQUE INTERNATIONAL	NM	M	54	45444
BIRMINGHAM	AL	M	55	43612
KAHULUI	HI	M	56	41794
SACRAMENTO METRO	CA	S	57	41637
NORFOLK REGIONAL	VA	M	58	41360
JACKSONVILLE INTL	FL	M	59	37207
WEST PALM BEACH	FL	M	60	35789
TUCSON	AZ	M	61	35167
DALLAS LOVE FIELD	TX	L	62	34985
RENO INTERNATIONAL	NV	M	63	34576
DES MOINES MUNICIPAL	IA	S	64	34271
BURBANK	CA	L	65	34235
RALEIGH DURHAM	NC	M	66	33749
WICHITA MID CONTINENT	KS	S	67	33367
SYRACUSE HANCOCK INTL	NY	M	68	33147
EL PASO INTERNATIONAL	TX	M	69	33006
GREENSBORO REGIONAL	NC	M	70	32284
ONTARIO	CA	S	71	31481
ROANOKE	VA	S	72	30279
SANTA ANA	CA	L	73	29834
RICHMOND BYRD INTL	VA	S	74	28864
ALBANY COUNTY	NY	M	75	27542
HOUSTON HOBBY	TX	L	76	27861
AUSTIN	TX	S	77	27409
SPOKANE INTERNATIONAL	WA	M	78	26972
SHREVEPORT	LA	S	79	26273
LIHUE	HI	M	80	26144
LITTLE ROCK ADAMS FIELD	AR	S	81	25559
GRAND RAPIDS	MI	S	82	25513
JACKSON MUN ARPT	MS	S	83	25418
KNOXVILLE MCGHEE TYSON	TN	S	84	24957
CHARLESTON AFB MUNICIPAL	SC	S	85	23621
MADISON	WI	S	86	23316
SIOUX FALLS FOSS FLD	SD	S	87	23202
GREEN BAY AUSTIN STRAUBEL	WI	S	88	22120
PROVIDENCE	RI	S	89	22065
MOLINE	IL	S	90	21778
BRISTOL TRI CITY	TN	S	91	21207
MOBILE BATES FIELD	AL	S	92	21194
COLUMBIA METROPOLITAN	SC	S	93	20870
HILO GENERAL LYMAN FIELD	HI	M	94	20749
PEORIA	IL	S	95	20688
BOISE	ID	S	96	20498
LUBBOCK	TX	S	97	20456
CHATTANOOGA	TN	S	98	19504
LINCOLN MUNICIPAL	NE	S	99	19182
GREER	SC	S	100	17309
HUNTSVILLE MADISON COUNTY	AL	S	101	17244
FRESNO AIR TERMINAL	CA	S	102	17056
LANSING	MI	S	103	17043
CHARLESTON	WV	S	104	16719
COLORADO SPRINGS	CO	S	105	16669
LEXINGTON	KY	S	106	16403
KONA KE AHOLE	HI	S	107	16218
BILLINGS	MT	S	108	16162
TOLEDO EXPRESS	OH	S	109	15775
SARASOTA BRADENTON	FL	S	110	15684
AKRON CANTON REGIONAL	OH	S	111	15580
CEDAR RAPIDS	IA	S	112	15566
AMARILLO	TX	S	113	15410
BATON ROUGE RYAN FIELD	LA	S	114	15061
SPRINGFIELD CAPITAL	IL	M	115	14854
ASHEVILLE	NC	S	116	14541
SIOUX CITY MUNICIPAL	IA	S	117	14474
TALLAHASSEE	FL	S	118	14164
MIDDLETON	PA	S	119	13846
SPRINGFIELD	MO	S	120	13846
FAIRBANKS	AK	S	121	13823
MIDLAND	TX	S	122	13683
DAYTONA BEACH	FL	S	123	13375
FORT SMITH MUNICIPAL	AR	M	124	13206
DULUTH	MN	S	125	13179
AUGUSTA	GA	S	126	13118
ROCHESTER	MN	S	127	12947
MONTGOMERY DANNELLY FIELD	AL	S	128	12857
HYANNIS	MA	M	129	12761
SOUTH BEND	IN	S	130	12725
FORT WAYNE	IN	S	131	12457
PORTLAND	ME	S	132	12440
COLUMBUS	GA	S	133	12292
FAYETTEVILLE GRANNIS	NC	S	134	12011
WATERLOO	IA	S	135	11992
SAGINAW TRI CITY	MI	S	136	11767
EVANSVILLE	IN	S	137	11673
MONTEREY	CA	S	138	11464
CORPUS CHRISTI	TX	S	139	11593
BURLINGTON INTERNATIONAL	VT	M	140	10823
FARGO HECTOR FIELD	ND	S	141	10769
ALLENTOWN	PA	S	142	10691
SAVANNAH MUNICIPAL	GA	S	143	10532
BANGOR INTERNATIONAL	ME	S	144	10293
FLINT BISHOP	MI	S	145	10277
CHAMPAIGN UNIV OF ILL	IL	M	146	10271
FORT MYERS PAGE FIELD	FL	S	147	10242
NANTUCKET MEMORIAL	MA	M	148	10235
SOUTH LAKE TAHOE	CA	M	149	10206
BISMARCK	ND	M	150	10174

FIGURE A-1
150 AIRPORTS SELECTED FOR RBX PLACEMENT FOR THEIR RANK BY AIR CARRIER OPERATIONS

TOWER	STATE	RANK BY TOTAL AC OPERA-TIONS	RANK BY AIR CARRIER OPERA-TIONS	TOWER	STATE	RANK BY TOTAL AC OPERA-TIONS	RANK BY AIR CARRIER OPERA-TIONS
LONG BEACH	CA	3	195	ATLANTA DEKALB PEACHTREE	GA	60	399
VAN NUYS	CA	4	427	FULLERTON MUNICIPAL	CA	63	376
OPA LOCKA	FL	7	394	MINNEAPOLIS FLYING CLOUD	MN	67	372
SEATTLE BOEING	WA	12	282	PALO ALTO	CA	68	397
TORRANCE MUNICIPAL	CA	13	423	SAN DIEGO BROWN FIELD	CA	69	411
SAN JOSE REID HILLVIEW	CA	14	409	SANTA MONICA	CA	70	415
HAYWARD	CA	16	384	CARLSBAD PALOMAR	CA	72	363
DENVER ARAPAHOE CNTY	CO	17	341	LA VERNE BRACKETT	CA	78	402
TAMIAMI	FL	18	421	BEDFORD	MA	79	287
ANCHORAGE MERRILL	AK	20	390	SANTA BARBARA	CA	80	194
CONCORD	CA	22	325	SACRAMENTO EXECUTIVE	CA	81	320
SAN DIEGO MONTGOMERY	CA	25	392	EL MONTE	CA	82	371
FT WORTH MEACHAM	TX	33	374	SCOTTSDALE	AZ	83	352
TULSA RIVERSIDE	OK	35	322	ATLANTA FULTON CNTY	GA	84	375
ISLIP MACARTHUR	NY	40	190	HOLLYWOOD	FL	87	385
NEW ORLEANS LAKEFRONT	LA	42	302	MORRISTOWN	NJ	89	389
FARMINGDALE	NY	43	373	NORWOOD	MA	92	333
DEER VALLEY	AZ	46	369	DALLAS ADDISON	TX	93	357
TETERBORO	NJ	47	280	ST PETERSBURG CLEARWATER	FL	95	283
PONTIAC	MI	48	310	DETROIT WILLOW RUN	MI	98	159
CHICAGO DU PAGE	IL	49	367	LIVERMORE MUNICIPAL	CA	99	386
CHICAGO PALWAUKEE	IL	50	406	VERO BEACH	FL	100	338
SAN DIEGO GILLESPI	CA	51	412	CHINO	CA	101	361
MELBOURNE	FL	52	170	EVERETT PAINE FIELD	WA	103	308
SAN CARLOS	CA	54	417	OXNARD VENTURA CNTY	CA	105	396

FIGURE A-2
50 AIRPORTS SELECTED FOR RBX PLACEMENT FOR THEIR RANK BY TOTAL AIRCRAFT OPERATIONS

		RANK AIR CARRIER	RANK TOTAL OPER.
Newport News	VA	158	134
Winston Salem	NC	160	275
Grand Forks Int'l	ND	162	128
Palm Springs Municipal	CA	164	277
Niagara Falls	NY	294	150
Pompano Beach Airpark	FL	400	161

The 151st ranked air carrier airport, also not included in the attached list, is Kalamazoo, Michigan. It has an air carrier annual operation rate of 9,844, approximately 27 daily. Although it seems that air carriers would have little involvement with one another at this rate, interactions with general aviation aircraft could necessitate manual or automatic on-board BCAS shut-off to avoid unnecessary alerts.

APPENDIX B

SYNCHRONOUS GARBLE

Synchronous garble is a term that refers to the overlapping of replies from two transponders when they are both replying to the same interrogation from a beacon radar. Today's ground beacon radar system operates by sending a two-pulse interrogation in a directional beam. The spacing of the two pulses varies to give the ground radar the capability to interrogate in several modes. Of importance to civil air traffic control are Modes 3/A and Mode C. In Mode 3/A, the interrogator asks the transponder to reply with its pilot-selected beacon code. This is one of 4096 different codes which is reported by the transponder as pulses in any of 12 pulse positions in the reply message. The beacon code is used by the radar to aid in associating a particular surveillance report with the established track for that aircraft. It is also used by the ATC computer to associate a flight plan with that track.

The Mode C reply also contains pulses in any of 12 pulse positions. This reply encodes the pressure altitude of the aircraft, rounded to the nearest 100 feet. With today's ATCRBS ground radar and the ATCRBS transponders, there is no way to cause a single aircraft to reply only to a single interrogation. All transponders reply to every interrogation which they hear. As a result, if two aircraft are within a radar beamwidth of each other and are within 1.65 nmi in slant range of each other, their replies will overlap when received by the ground radar. The pulse streams will overlap and the ground radar cannot be sure which pulses belong to which reply.

The ground radar makes interrogations at the rate of approximately 400 per second. With the radar beamwidth and radar scan rates used, this results in approximately 10-15 replies in one scan of the radar beam past the aircraft. The radar uses the continuous series of 10-15 replies to establish the azimuth of the aircraft. It marks the azimuth as the mean azimuth of the first and last reply of the series of replies. If two aircraft are separated in azimuth by about a beamwidth, they may have 2 or 3 replies each that garble, but may have 10 or 12 at the beginning or end of the series of replies that are clear. In some cases of azimuth separation like this, the radar may still be able to get clear replies.

But in general, synchronous garble can produce the following degrading effects for a ground radar:

1. A loss of range, azimuth and/or altitude data for one or both aircraft.

2. An incorrect 4096 beacon code for one or both aircraft.

3. An incorrect Mode C altitude readout for one or both aircraft.

4. An erroneous azimuth report for one or both aircraft.

Many examples of the effects of synchronous garble were observed in the Houston encounters. Some of these have appeared in earlier sections of this report. Figures 4-4 and 4-5 were two examples of garble. It is clear that when aircraft come close enough together to warrant instructions from a collision avoidance system, they are usually close enough to be in a synchronous garble situation.

The data presented here speaks eloquently against trying to generate collision avoidance resolution advisories from today's ATCRBS data. Reference 16 presents additional data showing the effects of synchronous garble. The new beacon radar which the FAA currently has under development called the Discrete Address Beacon System (DABS), Reference 17, is designed to eliminate the occurrence of synchronous garble. It does this with a new radar and new transponders which are designed so that only one aircraft at a time replies to an individual interrogation.

It should be pointed out that the BCAS system does not experience the synchronous garble in quite the same way as the ground radar. If one of the aircraft in these encounters were carrying BCAS, it would see the other's replies in the clear, unless there were a third aircraft at the same range. While BCAS also has a synchronous garble problem when the intruder is at a relatively great distance away, the severity of the problem decreases as the intruder aircraft comes closer in range. With the ground radar, the synchronous garble problem becomes worse as the aircraft get closer together.

APPENDIX C

DESCRIPTION OF THE MIDAIR COLLISIONS

This appendix is intended to provide additional detail to the 15 midair collision scenarios used in this study (Figures C-1 through C-15). The information includes date, location, altitude, type of aircraft and speeds involved. In addition, an estimation was made of the separations of the aircraft at 25 seconds before collision. (Unless otherwise noted, the aircraft are flying level.)

Date: 1/9/75

Place: Newport News, VA

Altitude: 1500 ft MSL

Approximate Separation 25 s before collision

Horizontal: 1.3 nmi
Vertical: 0 ft
Elevation Angle: 0 deg

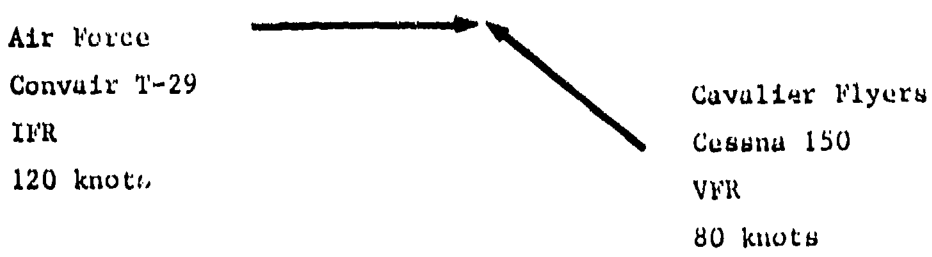


FIGURE C-1
MIDAIR NUMBER 1

Date: 9/9/69

Place: Fairland, IN

Altitude: 3,550 ft MSL

Approximate Separation 25 s before collision

Horizontal: 2.4 nmi
Vertical: 900 ft
Elevation Angle: 3.6 deg

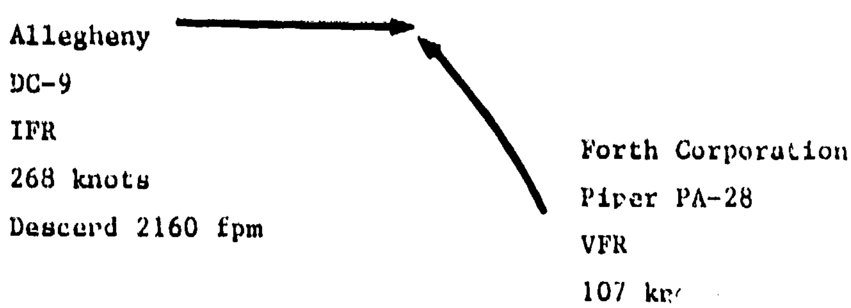


FIGURE C-2
MIDAIR NUMBER 2

Date: 1/9/75

Place: Whittier, CA

Altitude: 2538 ft MSL

Approximate Separation 25 s before collision

Horizontal: 1.2 nmi
Vertical: 120 ft
Elevation Angle: 1.0 deg

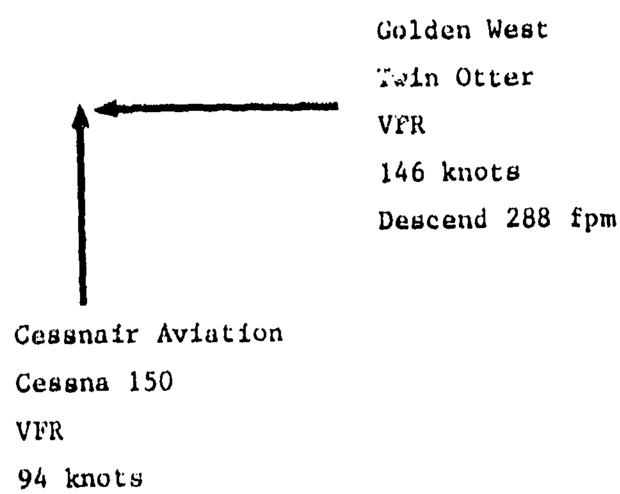


FIGURE C-3
MIDAIR NUMBER 3

Date: 6/29/72

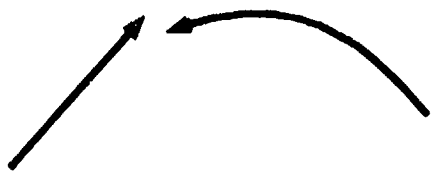
Place: Appleton, WI

Altitude: 2500 ft MSL

Approximate Separation 25 s before collision

Horizontal: 2.7 nmi
Vertical: 0 ft
Elevation Angle: 0 deg

North Central
Convair 580
VFR
260 knots
Turn



Air Wisconsin
De Havilland DHC-6
VFR
154 knots

FIGURE C-4
MIDAIR NUMBER 4

Date: 7/19/67

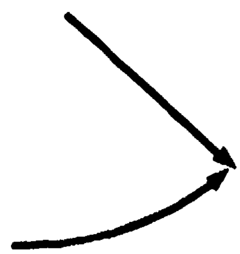
Place: Hendersonville, NC

Altitude: 6132 ft MSL

Approximate Separation 25 s before collision

Horizontal: 2.0 nmi
Vertical: 726 ft
Elevation Angle: 3.4 deg

Lanseair
Cessna 310
IFR
140 knots
Descend 317 fpm



Piedmont
B-707
IFR
245 knots
Climb 1425 fpm

FIGURE C-5
MIDAIR NUMBER 5

Date: 9/25/78

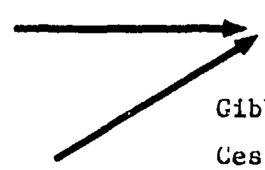
Place: San Diego, CA

Altitude: 3000 ft MSL

Approximate Separation 25 s before collision

Horizontal: 0.6 nmi
Vertical: 400 ft
Elevation Angle: 6.3 deg

Pacific Southwest
B-727
IFR
150 knots
Level;
Descend 350 fpm



Gibbs Flight Center
Cessna 172
IFR
80 knots
Climb 600 fpm

FIGURE C-6
MIDAIR NUMBER 6

Date: 8/8/68

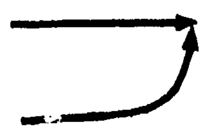
Place: Milwaukee, WI

Altitude: 2700 ft MSL

Approximate Separation 25 s before collision

Horizontal: 0.3 nmi
Vertical: 0 ft
Elevation Angle: 0 deg

North Central
Convair 580
IFR
200 knots
Descend 440 fpm;
Level; Climb 230 fpm



Home Airmotive
Cessna 150
VFR
84 knots
Turn

FIGURE C-7
MIDAIR NUMBER 7

Date: 3/9/67

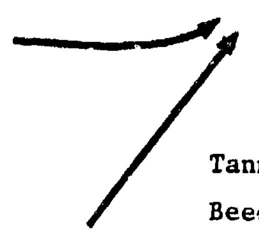
Place: Urbana, OH

Altitude: 4253 ft MSL

Approximate Separation 25 s before collision

Horizontal: 2.0 nmi
Vertical: 1458 ft
Elevation Angle: 6.9 deg

TWA
DC-9
IFR
342 knots
Descend 3500 fpm
Turn



Tann Company
Beechcraft Baron
VFR
171 knots

FIGURE C-8
MIDAIR NUMBER 8

Date: 7/24/76

Place: Huntsville, MO

Altitude: 6000 ft MSL

Approximate Separation 25 s before collision

Horizontal: 2.8 nmi
Vertical: 337 ft
Elevation Angle: 1.1 deg

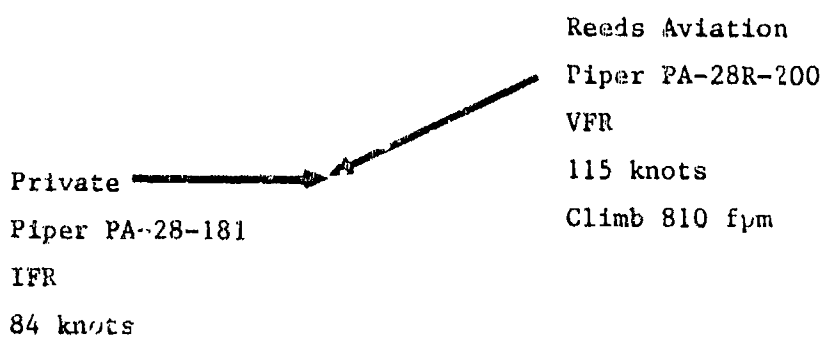


FIGURE C-9
MIDAIR NUMBER 9

Date: 6/12/68

Place: Denver, CO

Altitude: 9000 ft MSL

Approximate Separation 25 s before collision

Horizontal: 1.9 nmi
Vertical: 1460 ft
Elevation Angle: 7.5 deg

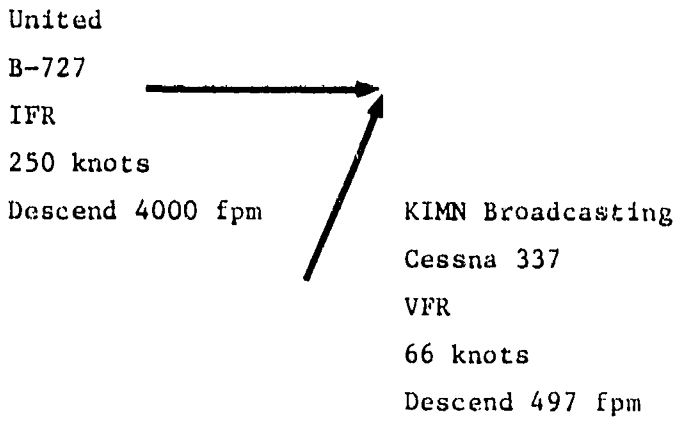


FIGURE C-10
MIDAIR NUMBER 10

Date: 10/11/74

Place: Saxis, VA

Altitude: 8500 ft MSL

Approximate Separation 25 s before collision

Horizontal: 2.0 nmi
Vertical: 0 ft
Elevation Angle: 0 deg

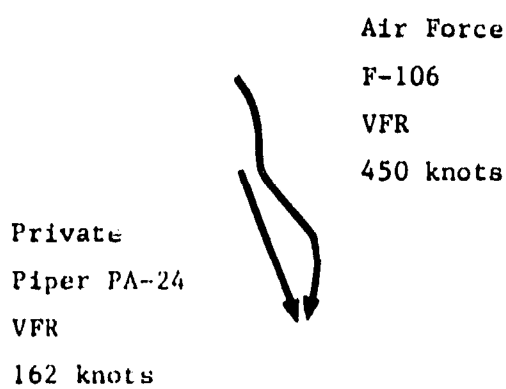


FIGURE C-11
MIDAIR NUMBER 11

Date: 11/12/79

Place: Kingston, UT

Altitude: 19,900 ft MSL

Approximate Separation 25 s before collision

Horizontal: 1.3 nmi
Vertical: 0 ft
Elevation Angle: 0 deg

Air Force
F-111
VFR
342 knots

Montana Power Company
Rockwell 690A
IFR
530 knots
Turn

FIGURE C-12
MIDAIR NUMBER 12

Date: 6/6/71

Place: Duarte, CA

Altitude: 15,150 ft MSL

Approximate Separation 25 s before collision

Horizontal: 3.6 nmi
Vertical: 625 ft
Elevation Angle: 1.6 deg

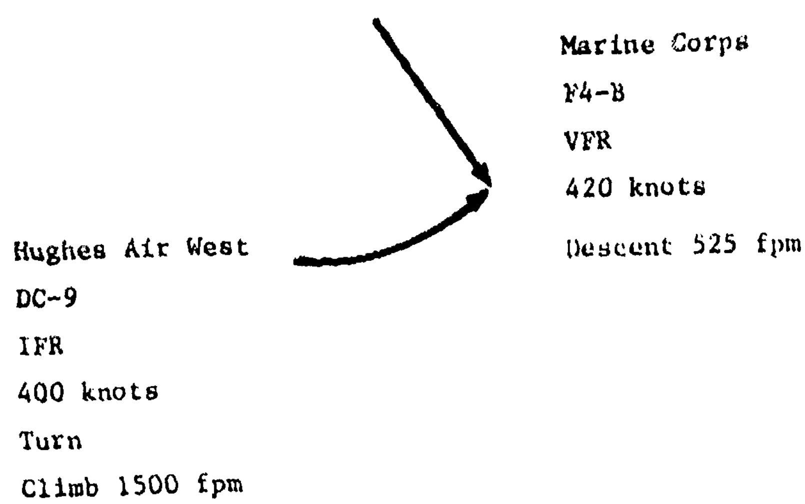


FIGURE C-13
MIDAIR NUMBER 13

Date: 12/4/65

Place: Carmel, NY

Altitude: 11,000 ft MSL

Approximate Separation 25 s before collision

Horizontal: 3.7 nmi
Vertical: 1667 ft
Elevation Angle: 4.3 deg

FIGURE C-14
MIDAIR NUMBER 14

Date: 3/27/68

Place: St. Louis, MO

Altitude: 1100 ft MSL

Approximate Separation 25 s before collision

Horizontal: 0.5 nmi
Vertical: 438 ft
Elevation Angle: 8.3 deg

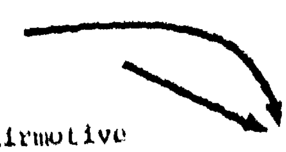


FIGURE C-15
MIDAIR NUMBER 15

APPENDIX D

LOCATION OF ALERTS RELATIVE TO THE HOUSTON TCA

The 64 positive alerts occurring with the recommended desensitization plan (Section 3.10) are shown plotted with their altitudes above ground level relative to the Houston TCA in Figures D-1 through D-3. In Figure D-1 the 20 ATC-ATC conflicts (40 aircraft) are shown for each performance level. Figure D-2 shows the 32 ATC-1200 conflicts, and Figure D-3 presents the 12 1200-1200 conflicts.

It is rather striking that within the TCA itself, the alert rate is very low. One sees that the preponderance of alerts occurs at low altitudes in the immediate vicinity of airports. For example, if one were to examine the probable alert rate for an IFR commercial route to Houston International, the data on which such determination would be made would exclude the low altitude (less than 5000 ft) non-TCA encounters, since that airspace would rarely be entered. If that were done, the alert rate of 1 in 19 hours for ATC-code aircraft would be significantly reduced. The number of alerts for these aircraft would change from 72 to 19, a reduction of almost 4:1.

HOUSTON TCA

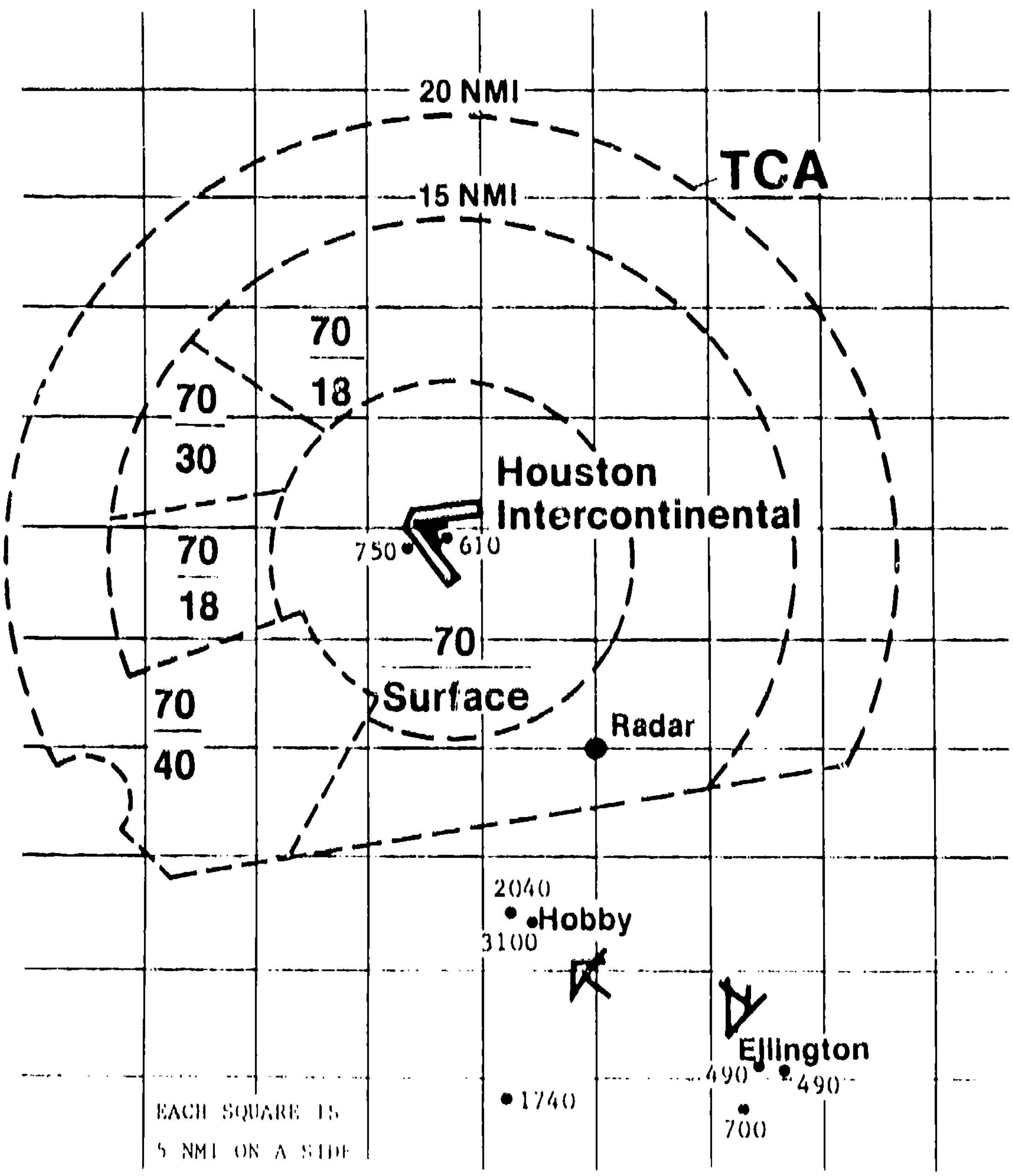


FIGURE D-1(a)
LOCATION OF PERFORMANCE LEVEL 3 POSITIVE ALERTS
BETWEEN TWO ATC-CODE AIRCRAFT

HOUSTON TCA

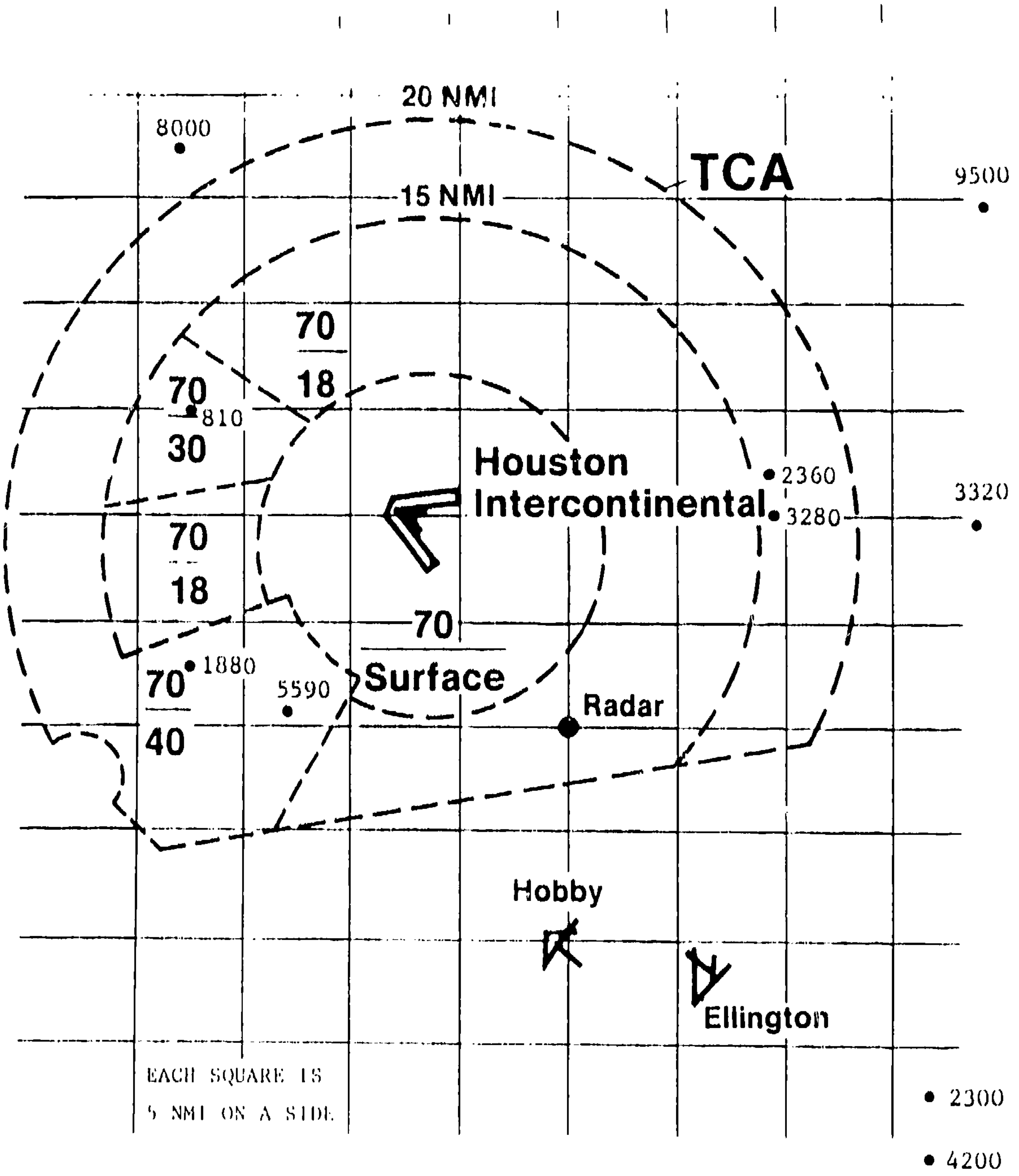


FIGURE D-1(b)
LOCATION OF PERFORMANCE LEVEL 4 POSITIVE ALERTS
BETWEEN TWO ATC-CODE AIRCRAFT

HOUSTON TCA

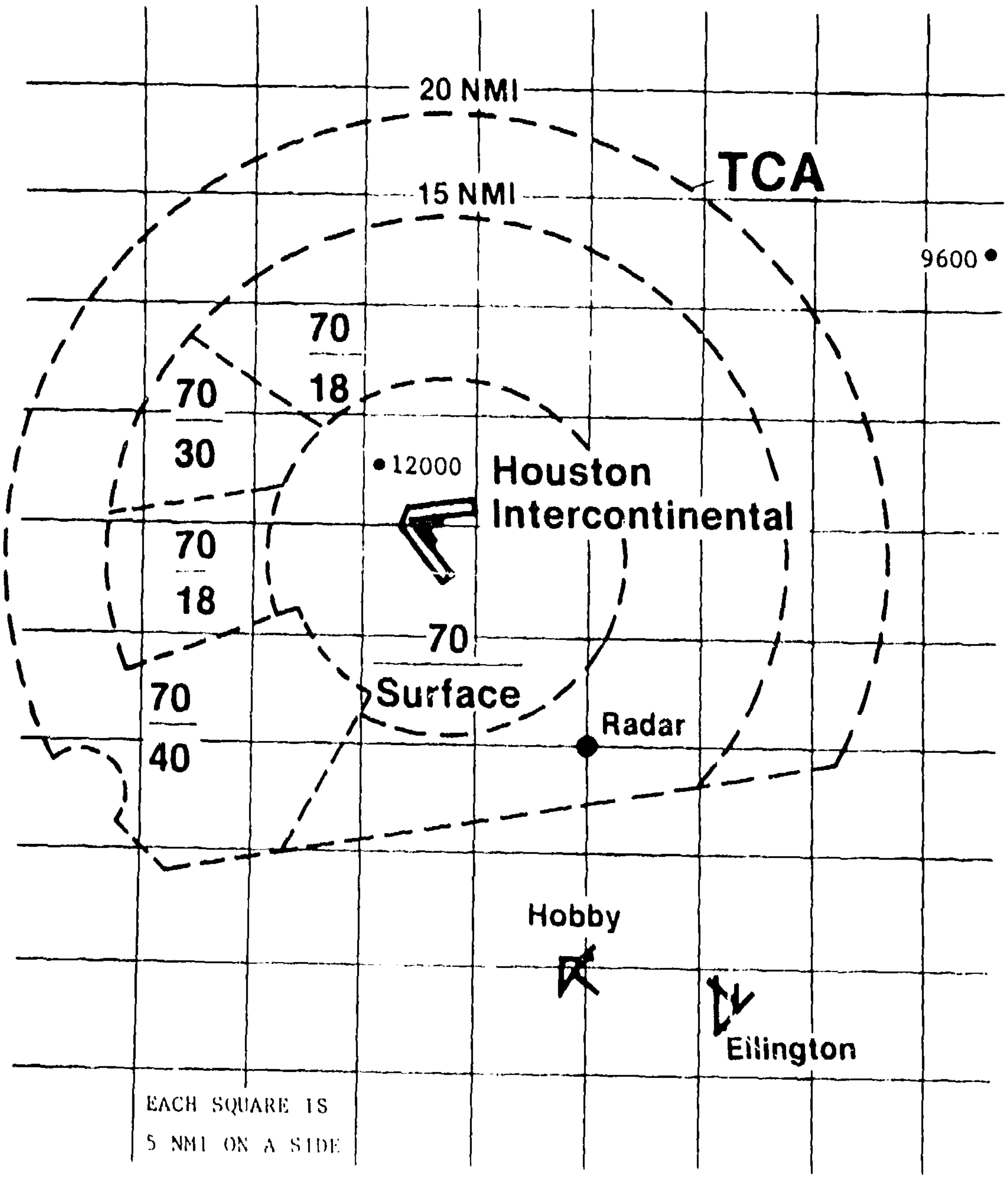


FIGURE D-1(c)
LOCATION OF PERFORMANCE LEVEL 5 POSITIVE ALERTS BETWEEN TWO ATC-CODE AIRCRAFT

HOUSTON TCA

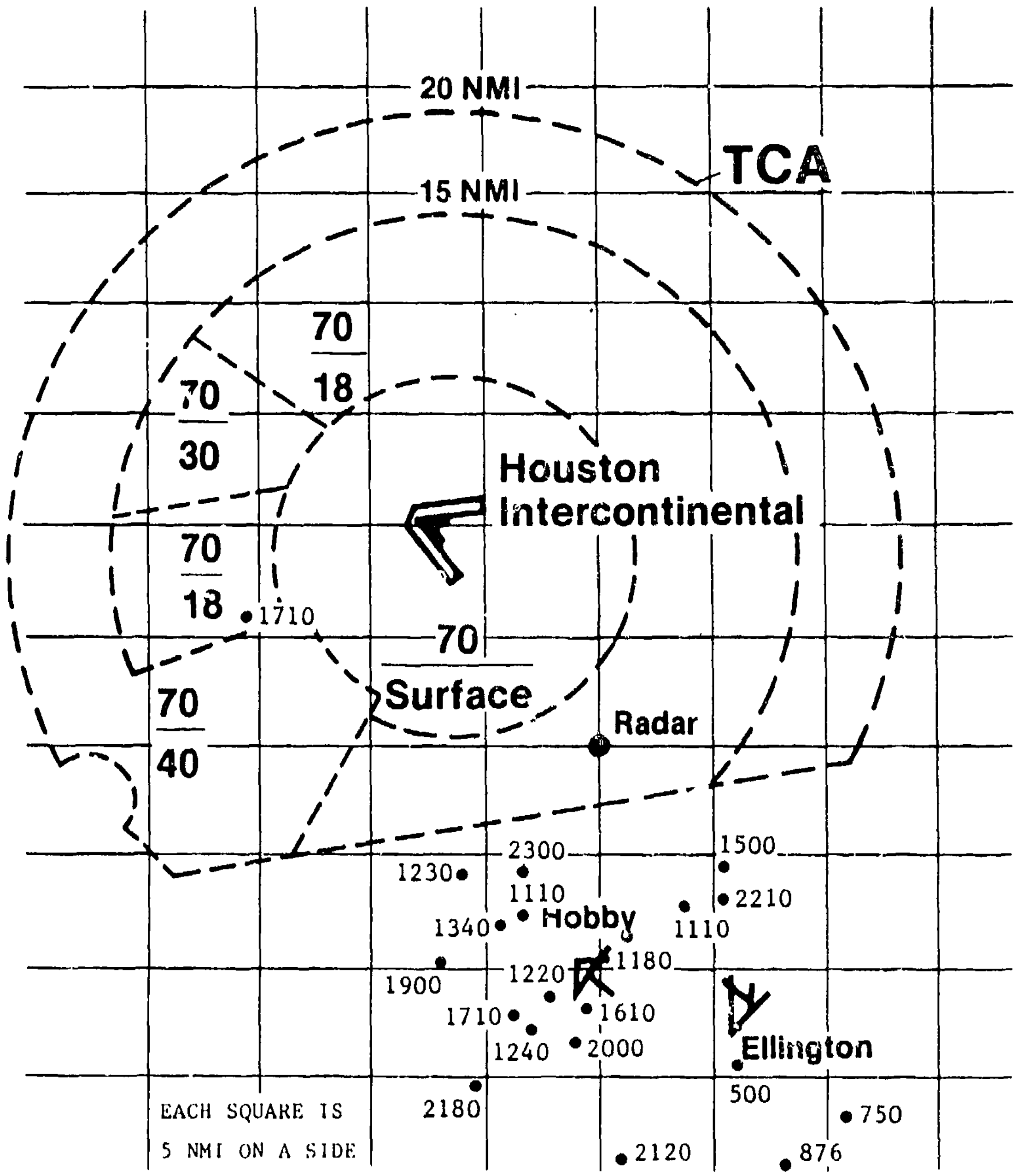


FIGURE D-2(a)
LOCATION OF PERFORMANCE LEVEL 3 POSITIVE ALERTS BETWEEN ONE ATC AND ONE 1200-CODE AIRCRAFT

HOUSTON TCA

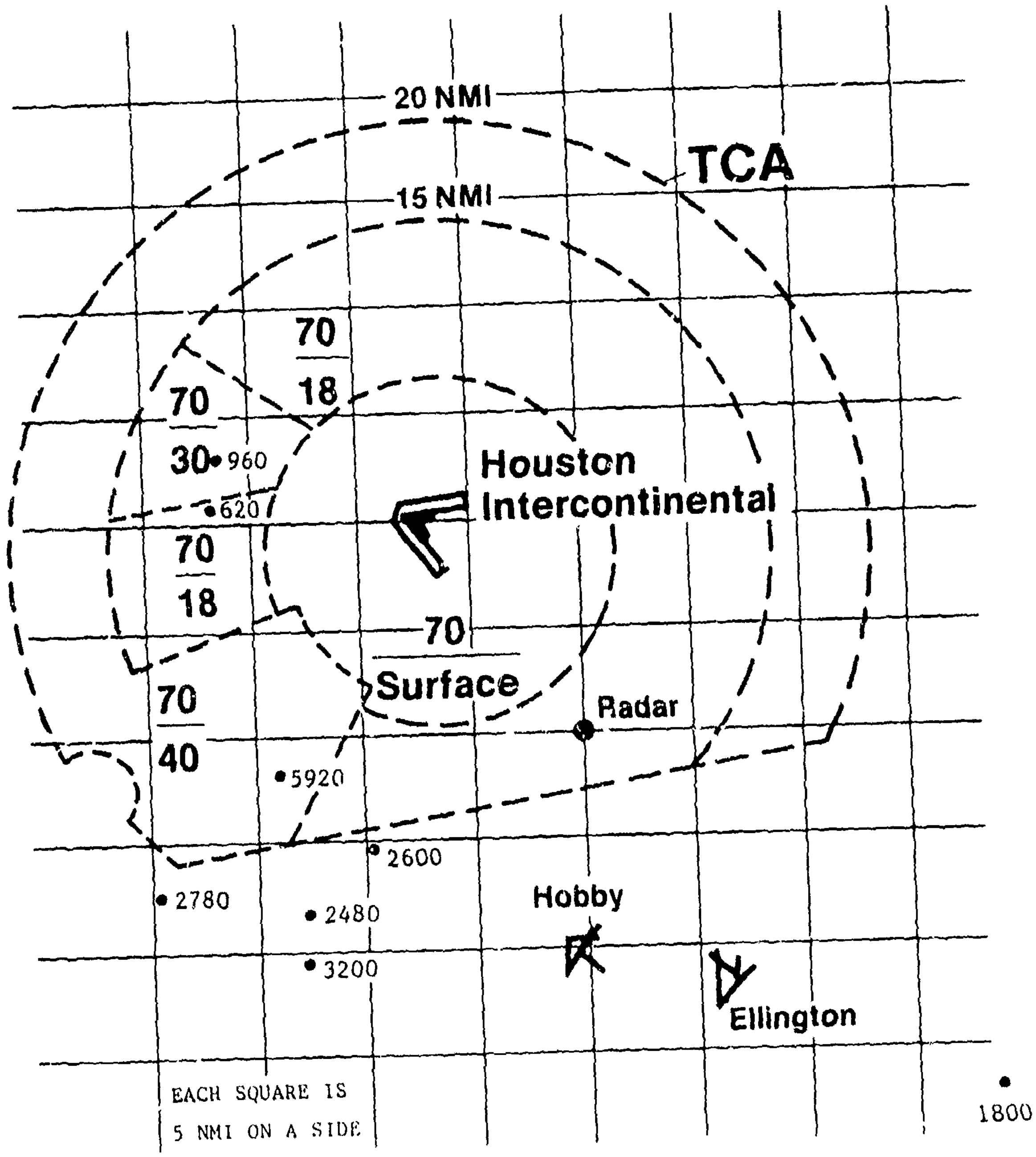


FIGURE D-2(b)
LOCATION OF PERFORMANCE LEVEL 4 POSITIVE ALERTS BETWEEN ONE ATC AND ONE 1200-CODE AIRCRAFT

HOUSTON TCA

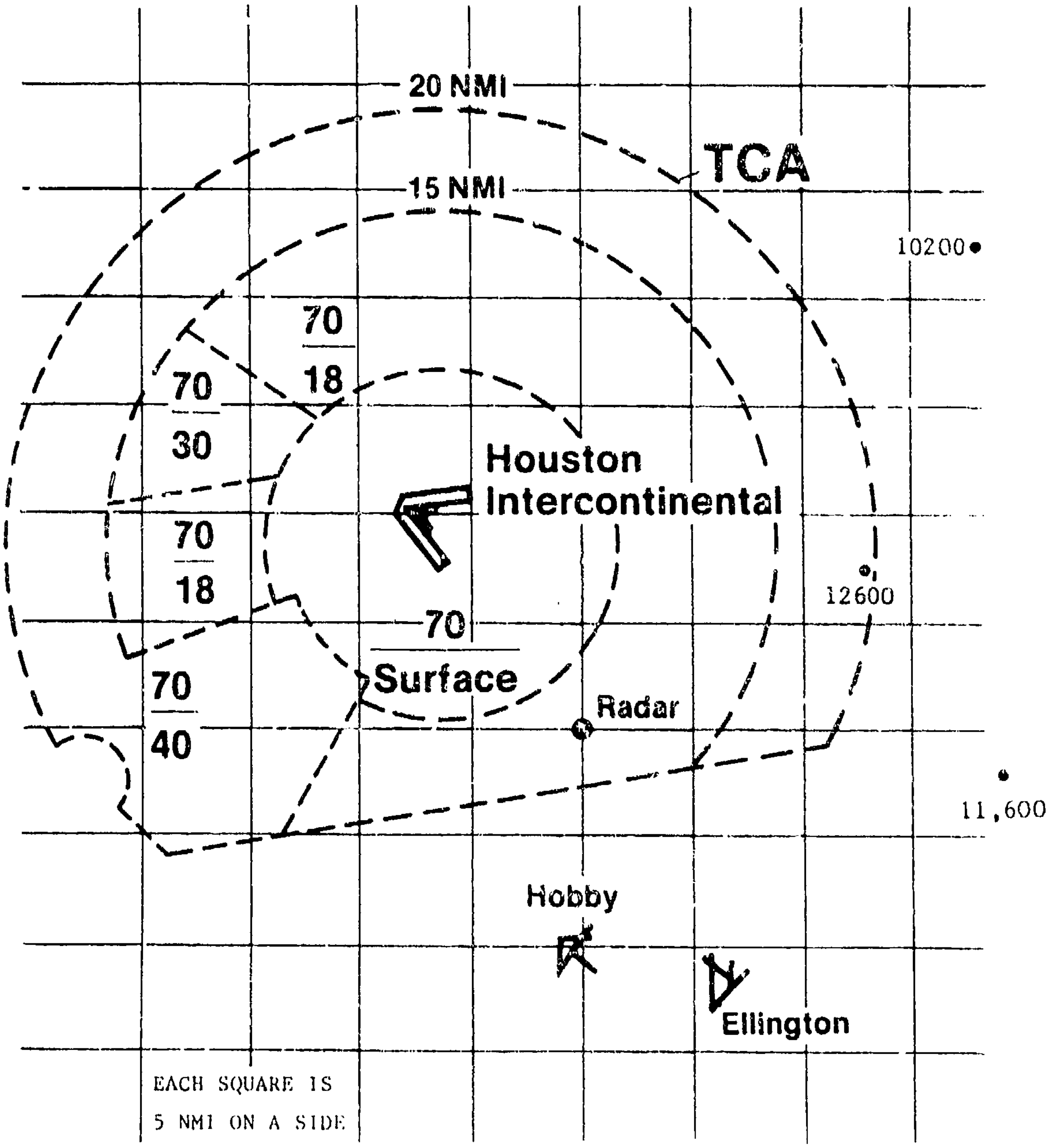


FIGURE D-2(c)
LOCATION OF PERFORMANCE LEVEL 5 POSITIVE ALERTS BETWEEN ONE ATC AND ONE 1200-CODE AIRCRAFT

HOUSTON TCA

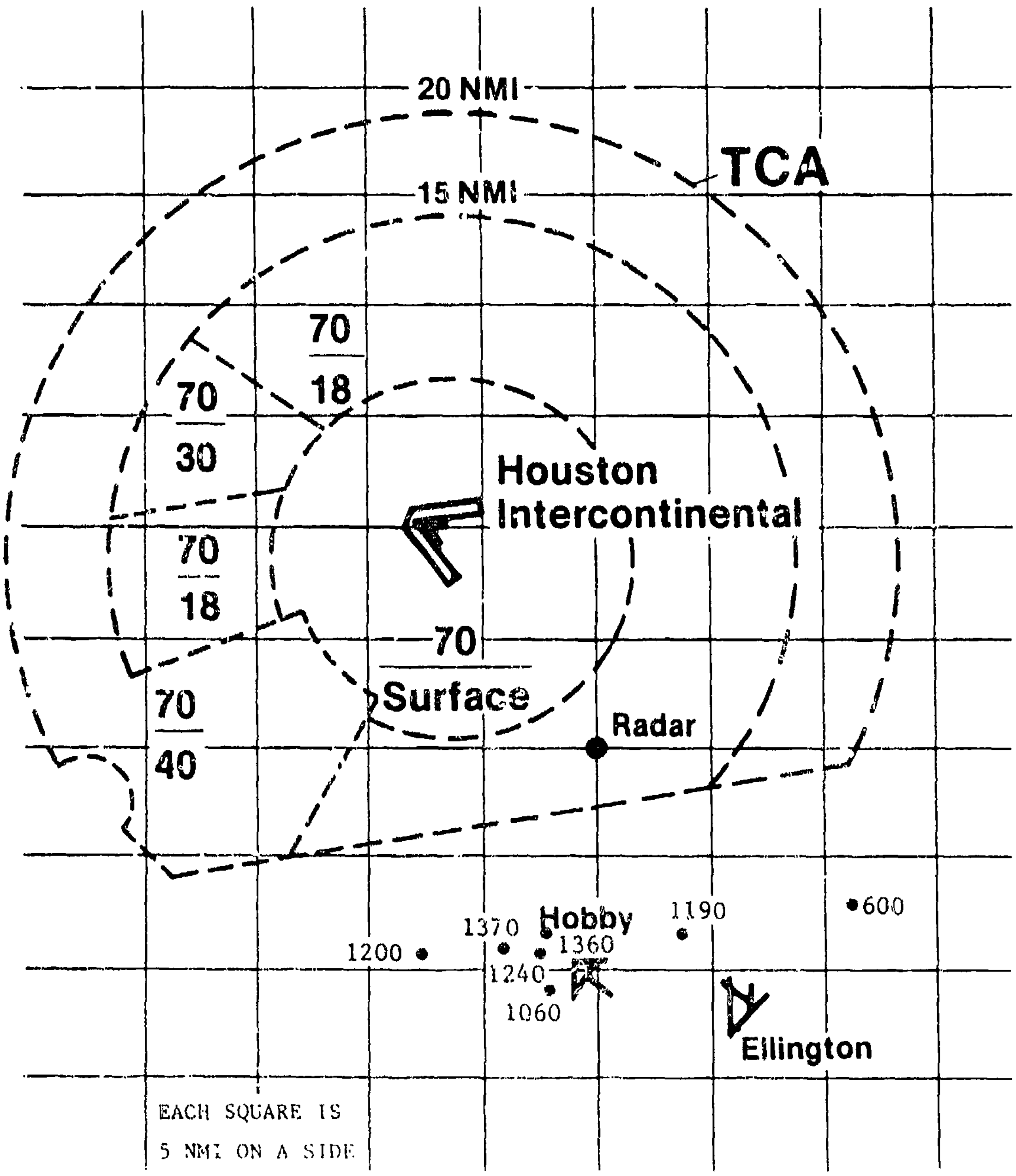


FIGURE D-3(a)
LOCATION OF PERFORMANCE LEVEL 3 POSITIVE ALERTS
BETWEEN TWO 1200-CODE AIRCRAFT

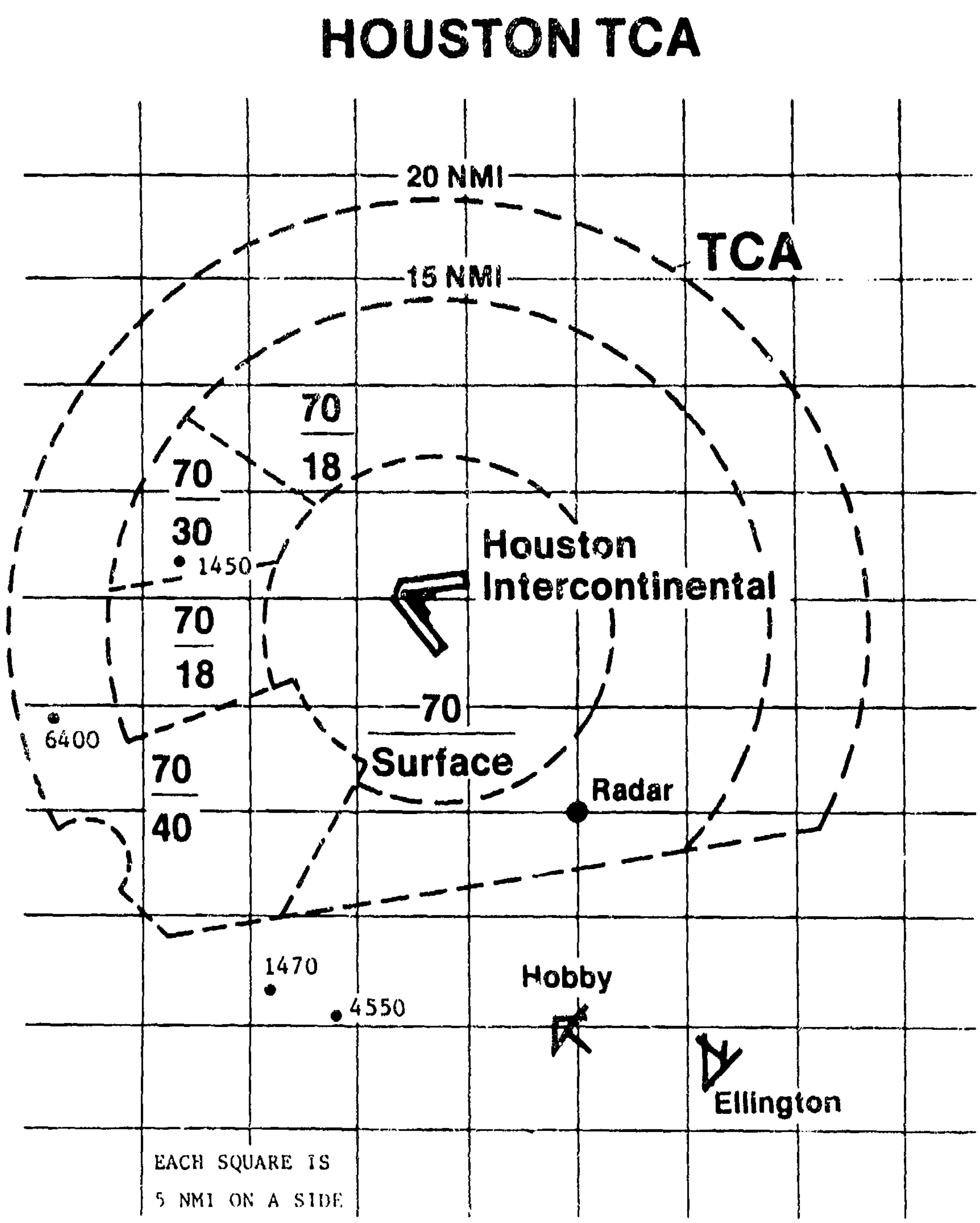
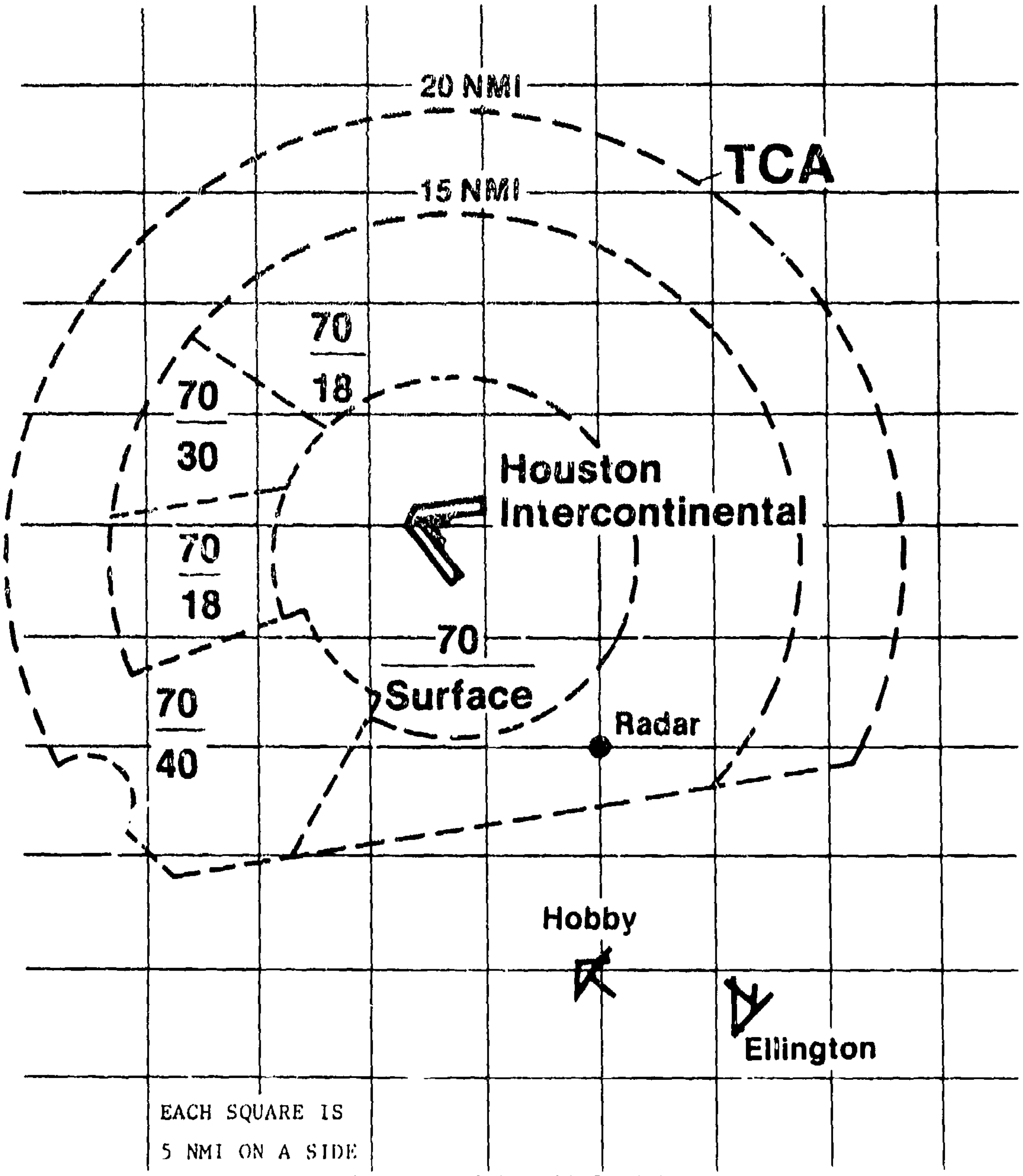


FIGURE D-3(b)
LOCATION OF PERFORMANCE LEVEL 4 POSITIVE ALERTS
BETWEEN TWO 1200-CODE AIRCRAFT

HOUSTON TCA



NO POSITIVE ALERTS OCCURRED IN THIS CATEGORY

FIGURE D-3(c)
LOCATION OF PERFORMANCE LEVEL 5 POSITIVE ALERTS
BETWEEN TWO 1200-CODE AIRCRAFT

APPENDIX E

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